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CIVIL ENGINEERING LABORATORY
Naval Construction Battalion Center
Port Hueneme, CA

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A STUDY OF THE EFFECTS OF INSULATION GAPS ON BUILDING HEAT LOSSES

April 1980

An Investigation Conducted by
JOHNS–MANVILLE SALES CORPORATION
Research & Development Center
Ken Caryl Ranch, Denver, CO 80217

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The scope of the program included testing of a wall panel designated Type I and a second designated Type II. The Type I panel consisted of 2x4 inch studs spaced 16 inches on center and insulated with R-11 fiberglass insulation. Tests were conducted in a Guarded Hot Box operated in accordance with ASTM C236-66 (Reapproved 1971). Thermal resistance values were determined at

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mean temperatures of approximately $45^{\circ}F$, $75^{\circ}F$, and $95^{\circ}F$. After these values were determined insulation areas amounting to 5, 10, and 15 percent of that originally installed were cut out from the mid-height of the test metering area and the tests repeated at each condition. The cut outs were to simulate omissions or errors in installation of the insulation.

The second wall panel, designated Type II, was constructed to simulate 2x6 inch studs spaced 24 inches on center and insulated with R-19 fiberglass insulation. The test program duplicated that performed on the R-11 insulated wall in order to determine whether the greater thickness gave similar changes in measured heat flow with increasing insulation void areas.

The test results showed heat flows significantly greater than the percentage of gaps in the insulation. At $45^{\circ}F$ mean temperature the loss in thermal resistance was more than three times the gap percentage up to a five percent gap for 2x4 inch stud walls. For 2x6 inch stud walls the loss was more than four times the gap percentage. For a 15 percent gap at $45^{\circ}F$ the loss increased to 38 percent.

TABLE OF CONTENTS

	Page
Summary	1
Panel Construction Details	3
Test Procedure	9
Test Results	15
Variability of Results	30
Analysis of Results	34
Conclusion	39
Appendix A - Photographic Illustrations	41
Appendix B - Summary of Report No. CR 78.006	59
Appendix C - Acknowledgements	60

SUMMARY

This program was funded by the U.S. Department of the Navy, Civil Engineering Laboratory, Naval Construction Battalion Center.

The scope of the program included testing of a wall panel designated Type I and a second designated Type II. The Type I panel consisted of 2 X 4 inch studs spaced 16 inches on center and insulated with R-11 fiber glass insulation. Tests were conducted in a Guarded Hot Box operated in accordance with ASTM C236-66 (Reapproved 1971). Thermal Resistance values were determined at mean temperatures of approximately 45°F, 75°F, and 95°F. After these values were determined insulation areas amounting to 5, 10, and 15 percent of that originally installed were cut out from the mid-height of the test metering area and the tests repeated at each condition. The cut outs were to simulate omissions or errors in installation of the insulation.

The second wall panel, designated Type II, was constructed to simulate 2 X 6 inch studs spaced 24 inches on center and insulated with R-19 fiber glass insulation. The test program duplicated that performed on the R-11 insulated wall in order to determine whether the greater thickness gave similar changes in measured heat flow with increasing insulation void areas.

The test results showed heat flows significantly greater than the percentage of gaps in the insulation. At 45°F mean temperature the loss in thermal resistance was more than three times the gap percentage up to a five percent gap for 2 X 4 inch stud walls. For 2 X 6 inch stud walls the loss was more than four times the gap percentage. For a 15 percent gap at 45°F the loss increased to 38 percent.

Conventional methods of calculation of surface-to-surface resistance values by parallel heat flow theory as presented in the 1977 ASHRAE Handbook of Fundamentals, Chapter 22, do not appear to be completely adequate when insulation gaps are involved. This appears to be contradictory to the conclusion in Report No. CR 78.006 (See Appendix B) which was based on a single gap size somewhat below 5 percent of the insulation area. The empirical results developed in this report may be used for that purpose until theory is developed which explains the phenomena.

A full discussion of the findings of the test program is presented in the Analysis and Conclusions sections of this report.

PANEL CONSTRUCTION DETAILS

The 16 inch on center, 2 X 4 inch stud panel, is designated Type I. Reference Test Panel No. 1 described in Report No. CR78.006, dated November 1977, was taken from storage and used for this program. The internal construction is shown in Figure 1.

The faces and the fiber glass insulation were inspected prior to test and not found damaged or displaced by shipment to storage and back.

In order to obtain a comparison of the effect of insulation gaps, it was proposed to cut out and test the same panel with gaps of 5, 10, and 15 percent sequentially after the panel had been tested without gaps. The area of insulation removed was based on the original net area of installed insulation. Thus, for a 32 inch wide metering area with two 1-1/2 inch wide studs in place, the insulation width was 32 - 3 = 29 inches. The insulated area was 48 x 29 = 1392 square inches and 5 percent was 69.6 square inches. Therefore, the gap height was 2.4 inches. The gap heights for 10 and 15 percent were 4.8 and 7.2 inches, respectively. The gaps were located at mid-height of the metering area. See photographs 7, 8, and 9.

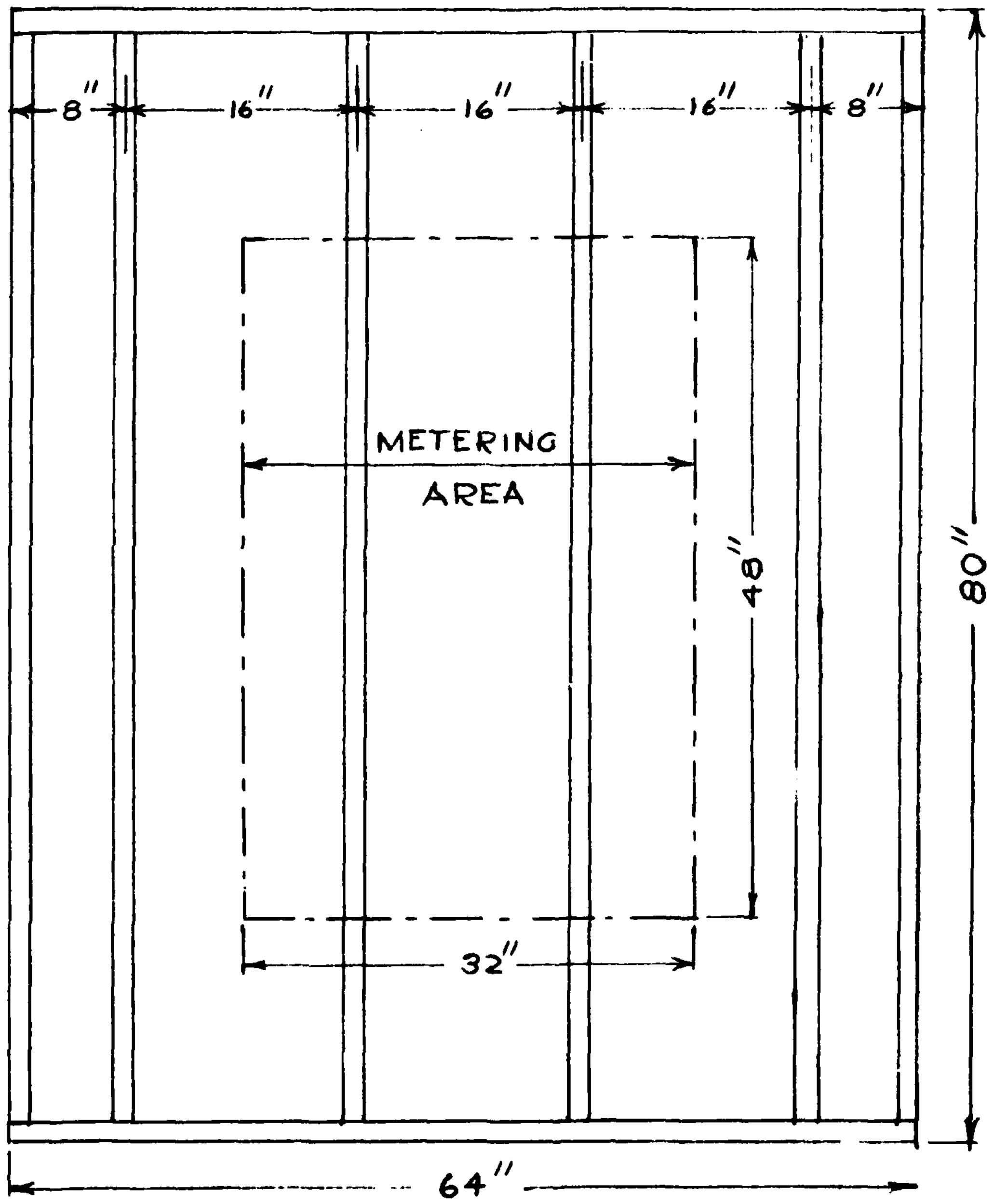
The gaps expresssed as a percentage of the insulation area were a lesser percentage of the gross wall area. Values for gross area would be as shown below:

TABLE 1
TYPE I PANEL
AREA - PERCENT OF TOTAL WALL

Insulation Gap	0%	5%	10%	15%
Insulation area	90.6	86.1	81.5	77.0
Gap area	0.0	4.5	9.1	13.6
Stud area	9.4	9.4	9.4	9.4
Total Wall Area	100.0	100.0	100.0	100.0

The simulated 24 inch on center, 2 X 6 inch stud panel designated as Type II, was constructed by placing two actual

FIGURE 1



FRAMING CONSTRUCTION TYPE I PANEL

Scale 1 in.= 12 in.

one inch wide studs 16 inches on center in the metering area (see Figure 2). This spacing of studs measured one inch wide gave the equivalent 6.25 percent stud to insulation width ratio that the nominal 2 inch (1.5 inch actual) stud attained when spaced 24 inches on center. The facings of wood fiber sheathing and gypsum board were from the same purchased lots as used for the Type I panel.

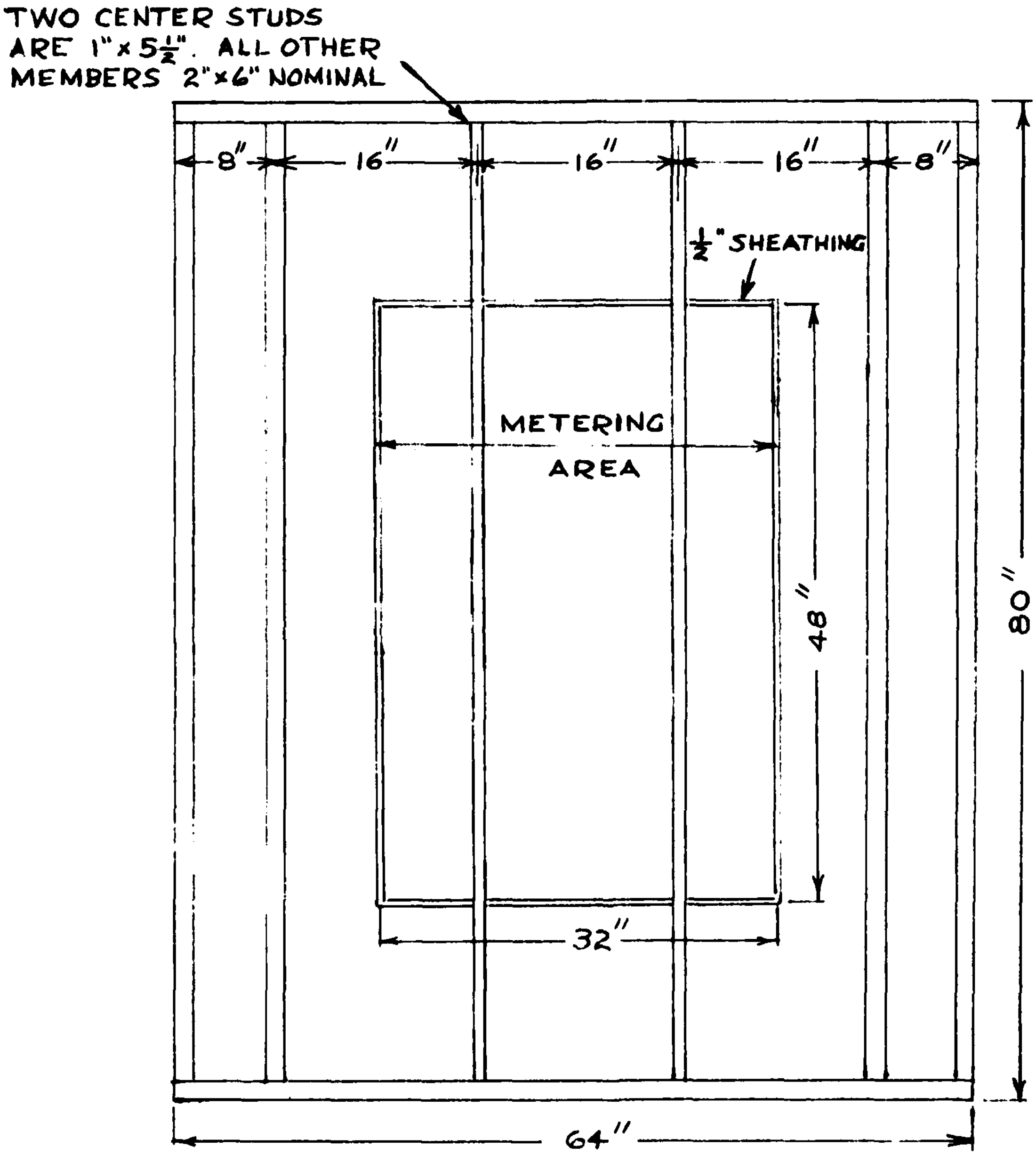
To reduce the possibility of air movement between the meter and guard areas through the 5-1/2 inch thick insulation, a perimeter of 1/2 inch wood fiber sheathing, as used for the panel exterior, was located around the metering area. This was not considered to be a potential problem with the Type I panel. To standardize the heat leakage caused by steel through fasteners for the wallboard and the sheathing, the sheathing was fastened with 1-1/4 inch F.H. wallboard screws spaced 6 inches vertically. The wallboard was fastened with 1-5/8 inch screws spaced 6 inches vertically. Spacing was arranged so the screws in the metering area were offset 3 inches from face to face. Each face was assembled with a 4 foot X 6 foot, 8 inch panel centered horizontally, and 8 inch edge strips.

The materials were recycled from the insulation, wallboard, sheathing and studs of the previous test program where ceiling panels using 2 X 6 joists had been tested. The 32 inch wide metering width was reduced by 2 inches (width of studs) to a 30 inch width of insulation. The total area was 32 X 48 = 1536 square inches and the insulation area was 30 X 48 = 1440 square inches. The heights of cut-out were kept at 2.4, 4.8, and 7.2 inches so the areas were 72, 144, and 216 square inches or still 5, 10 and 15 percent of insulation area. See Photographs 11, 12, 13, 14, and 15. Areas as a percent of the total area were:

TABLE 2
TYPE II PANEL
AREA - PERCENT OF TOTAL WALL

Insulation Gap Area	0%	5%	10%	15%
Insulation	93.7	89.0	84.3	79.6
Gap	0.0	4.7	9.4	14.1
Stud	6.3	6.3	6.3	6.3
Total	100.0	100.0	100.0	100.0

FIGURE 2



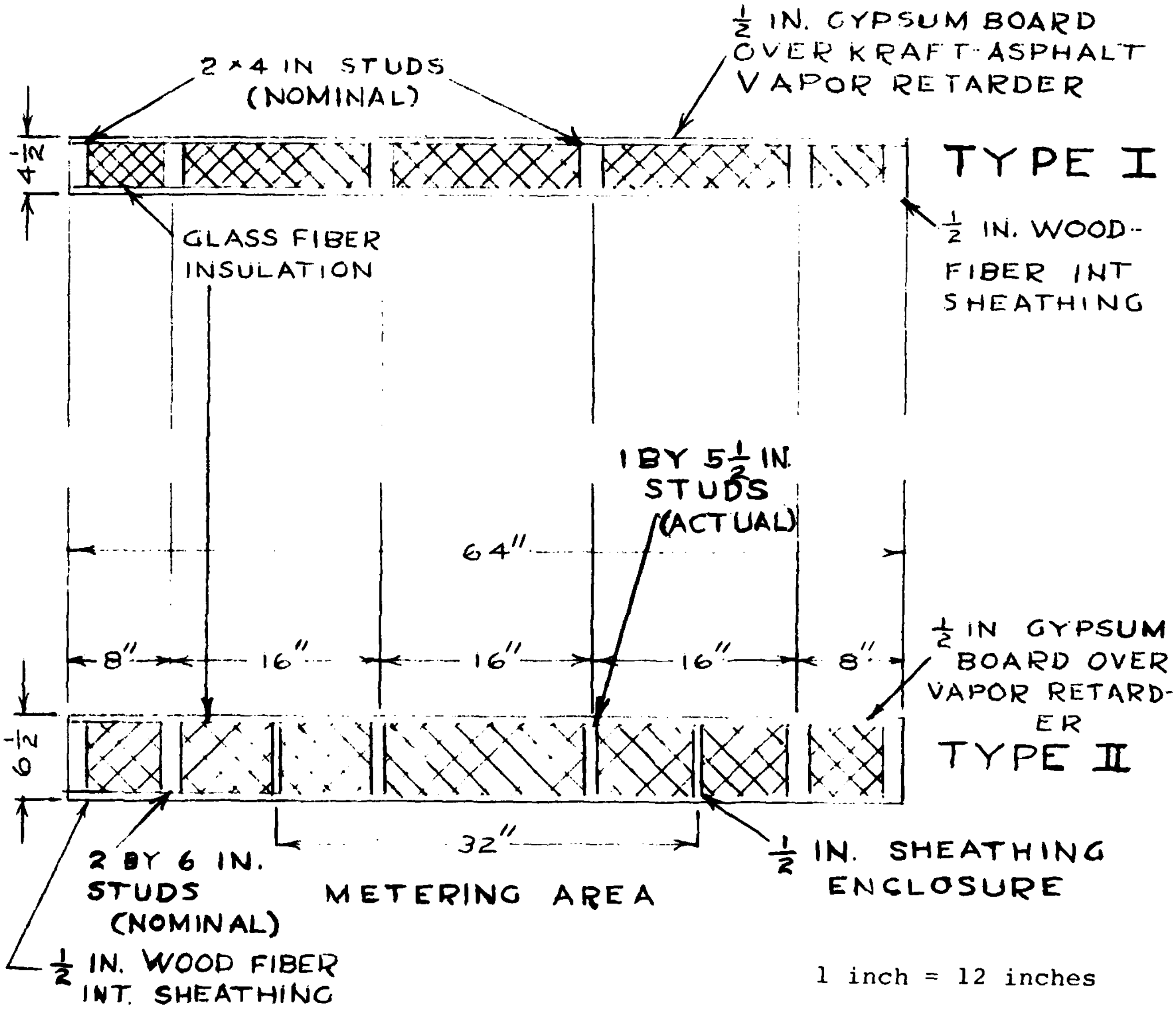
FRAMING CONSTRUCTION TYPE II PANEL

Scale 1 in.=12 in

To facilitate handling of both panels, eye bolts of 3/8 inch diameter stock and 1-1/8 inch opening were inserted at the midpoint of the upper edge of each panel.

Cross sectional drawings of the two panel types are presented in Figure 3. Details of the panels and the cut outs are shown in photographs 5 through 15 presented in Appendix A.

FIGURE 3



WALL CROSS SECTIONS

TEST PROCEDURE

The thermal performance of each panel was determined by the test procedure of ASTM C-236-66, Standard Test Method for Thermal Conductance and Transmittance of Built-up Sections by Means of the Guarded Hot Box. Figure 4, taken from ASTM C-236, shows the essential details of the Guarded Hot Box Test Apparatus.

Details of the Johns-Manville Research Center Guarded Hot Box are presented in the photographs in Appendix A. The exterior is presented in Photograph 1 and the controls are shown in Photograph 2. The interior view of the cold side enclosure is shown in Photograph 3. Photograph 4 shows the hot surface of the test panel and the hot side enclosure with the metering box and the guard area. The hot face of the panel with the gypsum wallboard center section removed is shown in Photograph 5. The cold face of the panel is presented in Photograph 16.

The metering box of the apparatus measures 32 X 48 inches and is 26 inches deep. The walls are 1-3/4 inches thick and are of sandwich construction, with a core of 2 pcf polyvinyl-chloride foam (Johns-Manville Vinylcel) with faces of glass reinforced polyester. The Guard Box is of the same construction with walls 4 inches thick. Electrical power to the metering box uses constant AC power to the low powered air circulation fans with manually adjusted DC power to resistance heaters as needed for the total required energy.

Prior to the start of the present test program, a standard specimen of roof insulation, tested previously at the laboratories of the National Research Council of Canada (NRC) and at the Johns-Manville Research Center, was installed and tested as a wall. The test history of that panel is shown in Table 3.

TABLE 3
TEST HISTORY OF CALIBRATION PANEL

Year	Location	Surface-To-Surface Thermal Resistance $^{o}F \cdot ft^2 \cdot hr/Btu$	Difference R Units	Difference Percent
1974	NRC	13.98	0	0
1975	J-M	13.80	-0.18	-1.3
1977	J-M	14.23	+0.25	+1.8
1978	J-M	14.69	+0.71	+5.1

The values are all adjusted to 40^o mean temperature.

FIGURE 4

GUARDED HOT BOX TEST APPARATUS

ASTM C 236

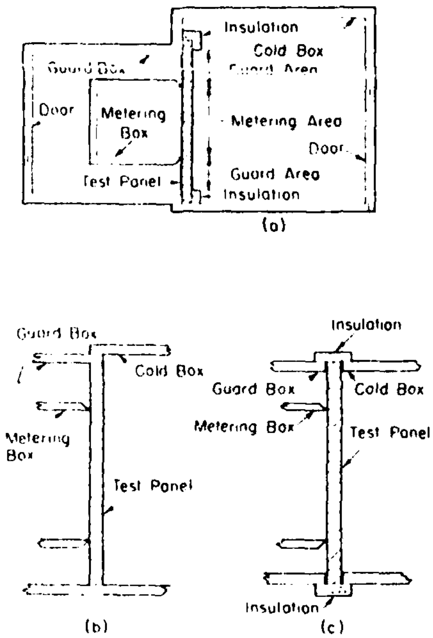


FIG. 1 General Arrangements of Test Box, Guard Box, Test Panel, and Cold Box

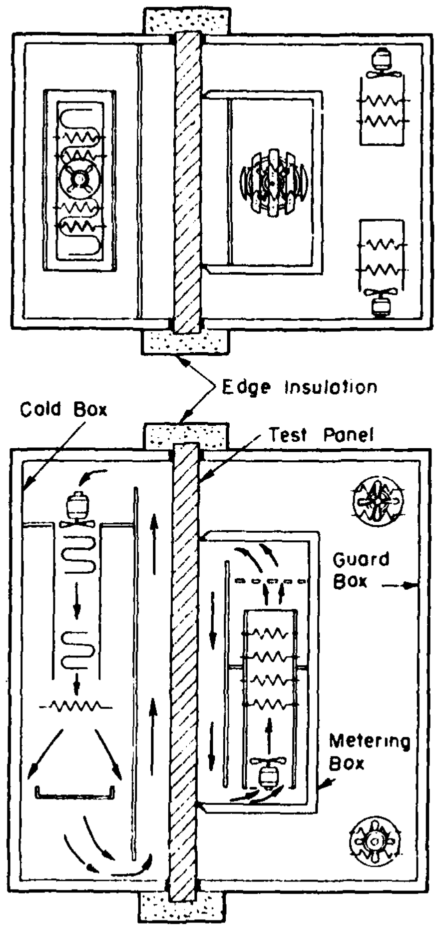


FIG. 2 Arrangement of Equipment During the Test.

The NRC test was conducted in their Calibrated Hot Box while the Johns-Manville tests were in the Guarded Hot Box.

The initial agreement was excellent. That obtained in 1977 was good. The 1978 value showed further drift. Adjustments to the apparatus were made during the period from the 1977 test to the 1978 test and the specimen was in storage at Johns-Manville for the period 1974 to 1979. This storage was in a heated building at 5750 feet altitude with a prevailing dry climate. The heating season indoor relative humidity is very low, 10 percent or less. The weather bureau records the mean annual outdoor humidity for Denver as 20 percent. It is possible that long term exposure to dry conditions and low (25 inch Hg) barometric pressure would change the thermal properties of hygroscopic materials. The 1975 to 1977 values and the 1978 values show a trend. In the absence of repeatability data for the Calibrated or Guarded Hot Boxes, the 5 percent variation is very reasonable.

The present panels were always tested in the same temperature sequence, from low to high temperature. Thus, the first tests were at 45°F mean temperature, then 75°F, followed by 95°F.

ASTM C-236 requires that temperature and heat flow equilibrium be demonstrated by requiring that thermal conductance be calculated from at least two sets of readings taken over a period of not less than four hours each, and that the values not differ by more than 1 percent. It was found necessary to extend this requirement to at least a third 4 hour period on another day to be assured of equilibrium. The mean temperature may have varied from one day to the next, but the values were considered justified if mean temperature corrections satisfied the requirements. This procedure was particularly important for the Type II panel due to its higher thermal resistance.

When calculating surface temperatures, weighted averages were considered for the different areas - insulation, studs, and voids - in order to arrive at the proper average temperatures. The percentages varied with area cutout.

In the 45°F and 75°F tests, the heat flow is assumed from the gypsum wallboard side to the wood fiber sheathing side. That is the typical scenario for winter conditions. The 45°F mean temperature condition represents average winter temperature conditions and the 75°F mean temperature is an approximate average value between winter and summer conditions. The value of

75°F mean was originally chosen only for convenience in testing and serves to compare materials. It has been test practice to have the direction of heat flow at 75°F mean temperature identical to winter conditions.

The 95°F mean temperature test represents summer conditions and, therefore, the direction of heat flow should be from the wood fiber sheathing side to the wallboard side. To give that direction of heat flow, the panel should be reversed face for face in the Guarded Hot Box. That is time consuming and undesirable unless necessary for valid results. After the Type I panel with no insulation cut-out was tested at 95°F, the panel was reversed and the test repeated with outer to inner surface heat flow to compare results.

As the test program continued, a secondary study was made to determine whether the exterior faces of the panels, the 1/2 inch sheathing and gypsum board, represented isothermal planes, or if parallel heat flow paths at the insulation, void, and stud areas resulted in a non-uniform temperature at the cold face.

At the time that the 10 percent area of insulation was removed, additional thermocouples were installed in order to provide added information on component temperatures.

Figure 5 shows thermocouple locations for the Type II wall. Crosses identify thermocouples. Numbers 1 through 11 were applied to the cold face of the panel, commonly the sheathing face. Numbers 14 through 24 were applied to the hot face, commonly the gypsum wallboard face.

In the gap area where thermocouples 6 and 19 were installed on the cold and hot outside surfaces, new thermocouples E and F were installed on the interior faces of the sheathing and wallboard where they were exposed to the air gap. For comparison, thermocouples A, B, C, and D were installed in the location 6 inches below the cut edge of the insulation; A and B on the outer and inner faces of the sheathing, and C and D on the inner and outer faces of the wallboard.

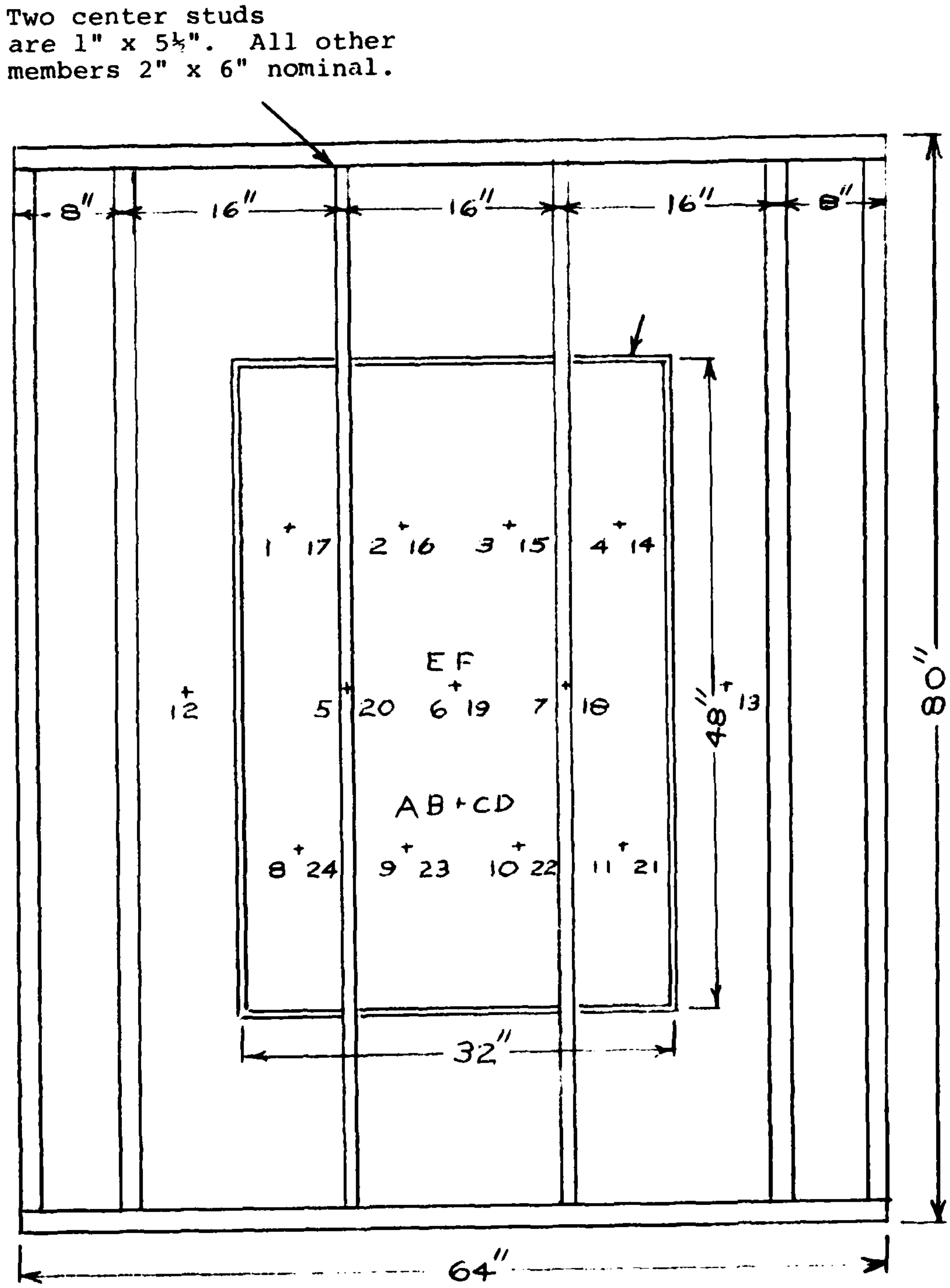
To measure resistance values for the panel components, specimens from the purchased lots of wood fiber sheathing and gypsum wallboard as well as the 2 X 6 inch wood studs were obtained. Two 12 X 12 X 1/2 inch sections of the sheathing and wallboard were tested in series at 1 inch total thickness at 75°F mean temperature in accordance with ASTM C-518. A composite

specimen of the wood was assembled by cutting flat grain specimens 12 X 1-1/2 X 1 inch and gluing the pieces together to form a 12 X 12 X 1 inch composite specimen. The direction of heat flow was, therefore, as it would be through the 2 X 6 inch stud assembled in a wall. That specimen was also tested at 75°F mean temperature in accordance with ASTM C-518.

In order to approximate the effect of temperature on thermal conductivity, the above three specimens were also tested in the Heat Meter Apparatus (ASTM C-518) at 120°F mean temperature.

Specimens of fiber glass insulation removed from the test panels were tested to ASTM C-518 for thermal resistance at 75°F and at the installed thicknesses of 3-1/2 and 5-1/2 inches. These determinations were made in a 36 X 36 inch Heat Meter Apparatus. Insulation sections removed from the center stud space were placed in the metering area of the heat meter.

FIGURE 5



THERMOCOUPLE LOCATIONS FOR TYPE II PANEL

Scale: 1 in. = 12 in.

TEST RESULTS

Detailed results are presented in Tables 4 to 9 for both types of wall. Table 10 gives a comparison of overall results on Type I wall while graphical presentation is made in Figure 6. Table 11 and Figure 7 present results for Type II. The tabular values are corrected to the desired mean temperatures.

Table 6 shows results for heat flow outward and for heat flow inward at 95°F mean temperature with no insulation cut-out. At mean temperatures differing by only 0.3°F, the thermal conductance reported to three decimal places was identical and the thermal resistance reported to decimal tenths differed by only one tenth or 0.9 percent. The results were judged to be so close that no significant difference existed. Therefore, the panels were not reversed in any of the subsequent tests.

The results of the tests on components of the panels are presented in Table 12.

Note that agreement with the ASHRAE design value is excellent for the sheathing and the value is comparable to the results of the previous Johns-Manville test. The agreement for values for gypsum wallboard and for fir is good. The difference for the fir seems due to the lower density. The difference for the wallboard is opposite to that indicated by density for ASHRAE value and as compared to the previous Johns-Manville test due to the 2.1 pcf higher density for the recent material. The difference is 7 percent.

A comparison of test results at 75°F and 120°F indicates no significant difference in values for the three materials. The slope of the temperature-resistance relationship between 75°F and 120°F is usually linear. For relatively high density insulation materials, such linearity should continue down to low temperature. From the present results, no significant variation would be expected.

The 1977 Fundamentals Volume of ASHRAE presents in Table 3B on Page 22.17, design value variation of the thermal conductivity of fiber glass blanket with temperature and density. Figure 8 was developed from that data to graphically show the variation with density and temperature. It is assumed the figures are

TABLE 4
MEASURED THERMAL RESISTANCE AT 45^{o}F OF R-11 INSULATED WALLS

	Fully Insulated	With mid-height voids of 5%	10%	15%
	Temperature - ^{o}F			
Heated Air	74.2	74.1	76.4	73.4
Hot Surface *	71.6	70.4	71.6	69.2
Cold Surface *	18.8	19.8	20.2	21.5
Cold Air	16.8	17.5	18.3	19.7
Surface to Surface, ΔT	52.8	50.6	51.4	47.7
Surface to Surface, mean	45.2	45.2	45.9	45.3
Thermal Conductance Btu/hr·ft^2·^{o}F	0.080	0.095	0.108	0.111
Thermal Resistance ^{o}F·ft^2·hr/BTU	12.4	10.6	9.2	9.0

* Area weighted average surface temperature

TABLE 5
MEASURED THERMAL RESISTANCE AT 75°F OF R-11
INSULATED WALLS

	Fully Insulated	With mid-height voids of 5%	10%	15%
	Temperature - °F			
Heated Air	103.9	103.8	106.4	105.1
Hot Surface *	101.3	100.1	101.8	100.8
Cold Surface *	50.8	51.5	50.8	50.3
Cold Air	49.0	49.0	48.7	48.2
Surface to Surface, ΔT	50.5	48.6	51.0	50.5
Surface to Surface, mean	76.0	73.5	76.3	75.4
Thermal Conductance Btu/hr·ft^2·°F	0.087	0.102	0.112	0.119
Thermal Resistance °F·ft^2·hr/BTU	11.6	9.8	8.9	8.4

* Area weighted average surface temperature

TABLE 6
MEASURED THERMAL RESISTANCE AT 95°F OF R-11
INSULATED WALLS

	Fully Insulated		With mid-height voids of 5%	10%	15%
	HFO*	HFI**	Temperature - °F		
Heated Air	127.3	127.8	125.3	128.7	123.7
Hot Surface ***	124.5	124.9	121.4	123.7	119.3
Cold Surface ***	71.1	72.1	70.7	69.4	68.2
Cold Air	69.2	70.5	68.4	67.2	66.0
Surface to Surface, ΔT	53.4	52.8	50.7	54.3	51.1
Surface to Surface, mean	98.2	98.5	96.0	96.6	93.8
Thermal Conductance Btu/hr·ft^2·°F	0.093	0.093	0.109	0.117	0.125
Thermal Resistance °F·ft^2·hr/BTU	10.8	10.7	9.2	8.6	8.0

* HFO = Heat flow outward, as in winter

**HFI = Heat flow inward, as in summer.

All data with voids was determined with heat flow outward only as these data indicate no significant difference in thermal properties with heat flow in either direction.

*** Area weighted average surface temperature

TABLE 7
MEASURED THERMAL RESISTANCE AT 45°F OF R-19
INSULATED WALLS

	Fully Insulated	With mid-height voids of 5%	10%	15%
	Temperature - °F			
Heated Air	75.2	69.7	71.5	68.5
Hot Surface *	73.2	66.1	67.3	64.3
Cold Surface *	20.7	19.2	19.1	19.4
Cold Air	19.4	17.4	17.1	17.4
Surface to Surface, ΔT	52.5	47.7	48.2	44.9
Surface to Surface, mean	47.1	43.1	43.2	41.8
Thermal Conductance Btu/hr·ft^2·°F	0.056	0.068	0.078	0.087
Thermal Resistance °F·ft^2·hr/BTU	18.0	14.6	12.8(5)	11.5

* Area weighted average surface temperature

NOTE: (5) refers to data items whose second significant decimal value was 5, and where the first significant decimal value was not rounded upward or downward.

TABLE 8
MEASURED THERMAL RESISTANCE AT 75°F OF R-19
INSULATED WALLS

	Fully Insulated	With mid-height voids of 5%	10%	15%
		Temperature - °F		
Heated Air	104.8	106.1	109.3	102.7
Hot Surface *	102.6	102.9	104.6	98.1
Cold Surface *	50.3	51.5	51.3	47.3
Cold Air	49.0	49.5	49.0	45.0
Surface to Surface, ΔT	52.3	51.5	53.3	50.8
Surface to Surface, mean	76.6	77.2	78.0	72.7
Thermal Conductance Btu/hr·ft^2·°F	0.0609	0.077	0.087	0.098
Thermal Resistance °F·ft^2·hr/BTU	16.4	13.1	11.5(5)	10.2

* Area weighted average surface temperature

NOTE: (5) refers to data items whose second significant decimal value was 5, and where the first significant decimal value was not rounded upward or downward.

TABLE 9
MEASURED THERMAL RESISTANCE AT 95°F OF R-19
INSULATED WALLS

	Fully Insulated	With mid-height voids of 5%	10%	15%
		Temperature - $^{\circ}$F		
Heated Air	126.9	127.9	128.3	128.1
Hot Surface *	124.6	124.4	123.6	123.2
Cold Surface *	71.1	70.3	70.1	69.3
Cold Air	69.8	68.3	67.9	66.9
Surface to Surface, ΔT	53.5	54.1	53.5	53.9
Surface to Surface, mean	97.8(5)	97.6(5)	96.6(5)	96.2(5)
Thermal Conductance Btu/hr·ft^2·$^{\circ}$F	0.065	0.082	0.092	0.103
Thermal Resistance $^{\circ}$F·ft^2·hr/BTU	15.4	12.2	10.9(5)	9.7

* Area weighted average surface temperature

NOTE: (5) refers to data items whose second significant decimal value was 5, and where the first significant decimal value was not rounded upward or downward.

TABLE 10
THERMAL RESISTANCE OF TYPE I WALLS
WITH NON-INSULATED AREAS
($^{o}F \cdot ft^{2} \cdot hr/BTU$)

	Percentage of Non-Insulated Area			
Mean Temperature, ^{o}F	0	5	10	15
45	12.4	10.6	9.3	9.0
75	11.6	9.8	8.9	8.4
95	10.9	9.2	8.6	8.0

TABLE 11
THERMAL RESISTANCE OF TYPE II WALLS
WITH NON-INSULATED AREAS
($^{o}F \cdot hr \cdot ft^{2}/BTU$)

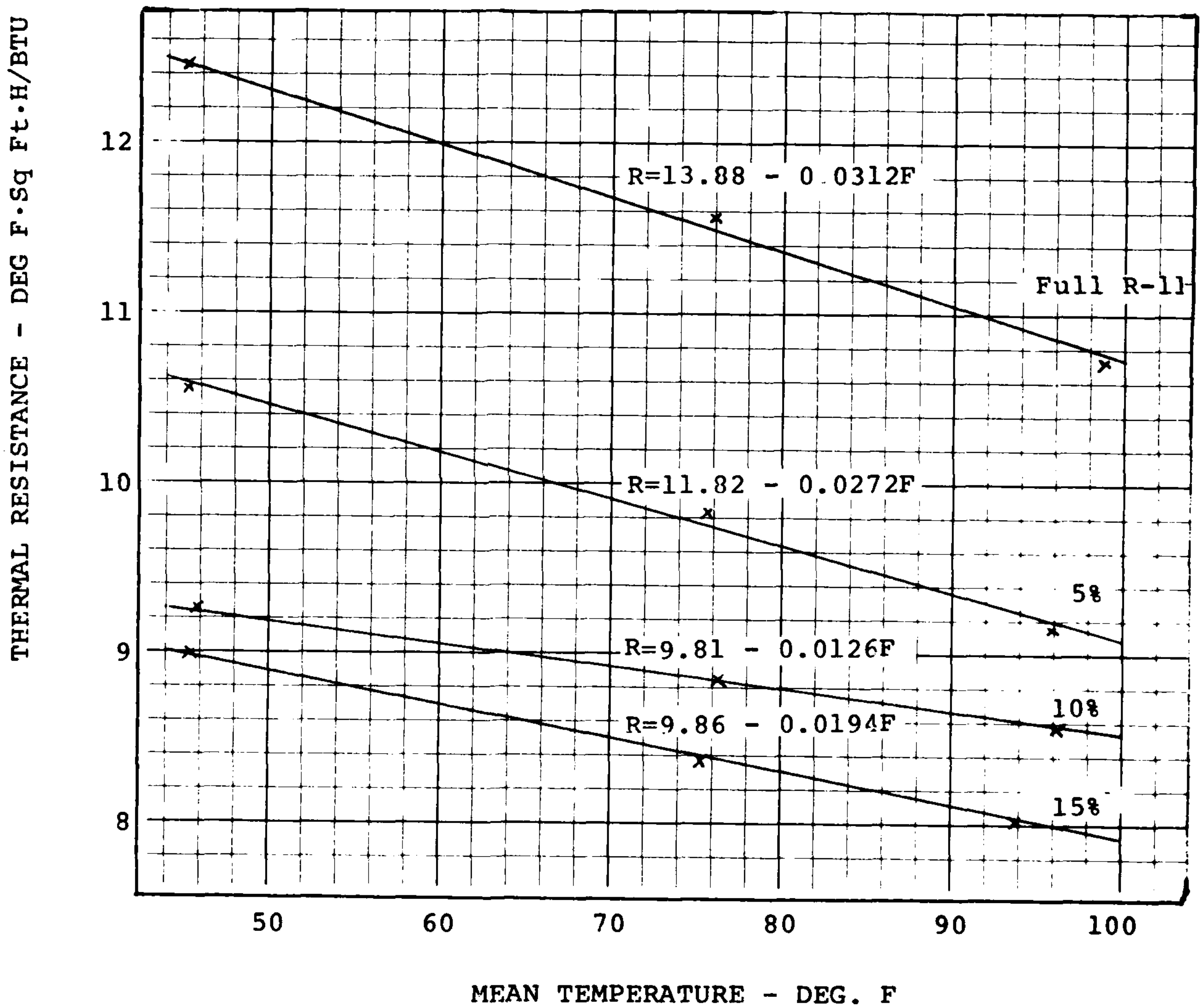
	Percentage of Non-Insulated Area			
Mean Temperature, ^{o}F	0	5	10	15
45	18.0	14.5	12.8	11.3
75	16.5	13.2	11.7	10.3
95	15.5	12.3	11.0	9.7

FIGURE 6

RELATIONSHIP OF THERMAL RESISTANCE

AND MEAN TEMPERATURE FOR VARIOUS GAP AREAS

TYPE I WALLS



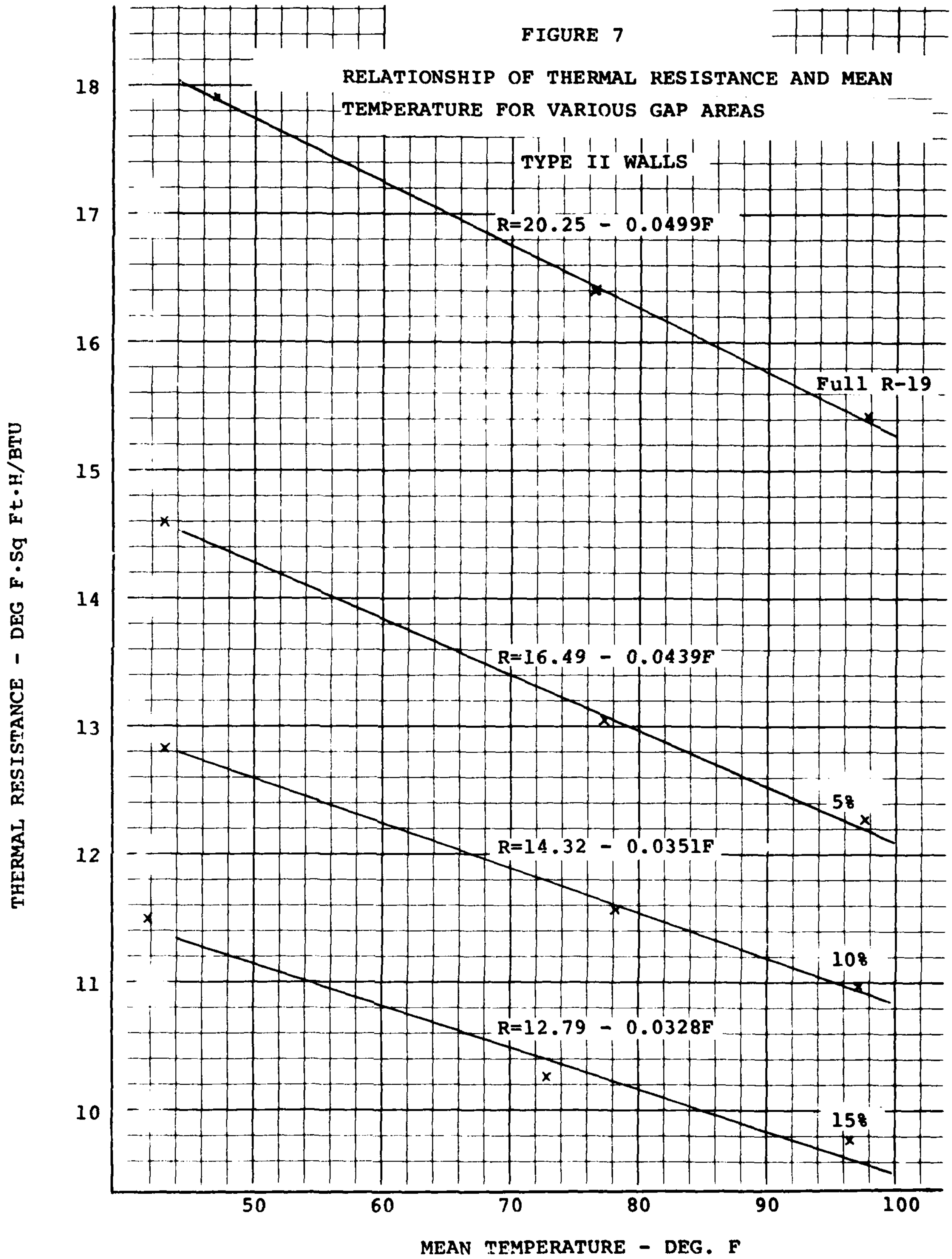


FIGURE 7
RELATIONSHIP OF THERMAL RESISTANCE AND MEAN TEMPERATURE FOR VARIOUS GAP AREAS
TYPE II WALLS
R=20.25 - 0.0499F
Full R-19
R=16.49 - 0.0439F
5%
R=14.32 - 0.0351F
10%
R=12.79 - 0.0328F
15%
THERMAL RESISTANCE - DEG F.Sq Ft.H/BTU
18
17
16
15
14
13
12
11
10
50
60
70
80
90
100
MEAN TEMPERATURE - DEG. F

TABLE 12

THERMAL CONDUCTIVITY AND RESISTANCE OF PANEL COMPONENTS

Mean Temperature °F	Source	Sheathing Thermal λ*	Sheathing Thermal R	Sheathing Thickness inches	Sheathing Density pcf	Gypsum Wallboard Thermal Resistance	Gypsum Wallboard Thickness inches	Gypsum Wallboard Density pcf	Clear Fir Thermal λ*	Clear Fir Thermal R	Clear Fir Thickness inches	Clear Fir Density pcf
75	Rpt CR78.006	0.42	1.02	0.43	22.5	0.41	0.495	40.9	0.81	1.80	1.46	27.6
	Present tests	0.42	2.17	0.910	22.8	0.76(5)	0.994	43.0	0.77	1.34	1.033	28.1
	****	----	1.02	0.43	----	0.38	0.495	----	----	1.90	1.46	----
	****	----	1.19	0.50	----	0.39	0.50	----	----	1.95	1.50	----
	ASHRAE	----	1.22	0.50	22.0	0.45	0.50	50.0	0.80	1.89	1.50	32.0
120	Present tests	0.43	2.107	0.906	22.8	0.83	0.999	43.0	0.78	1.33	1.035	28.1
	****	----	1.01	0.43	----	0.41	0.495	----	----	1.88	1.46	----

Mean Temperature °F	Source	Fiber Glass Blanket - Type I Thermal Resistance	Fiber Glass Blanket - Type I Thickness inches	Fiber Glass Blanket - Type I Density pcf	Fiber Glass Blanket - Type II Thermal Resistance	Fiber Glass Blanket - Type II Thickness inches	Fiber Glass Blanket - Type II Density pcf
75	CR78.006	11.3	3.50	0.71	---	---	---
	Present Tests	11.87**	3.50	0.79	19.33***	5.50	0.87

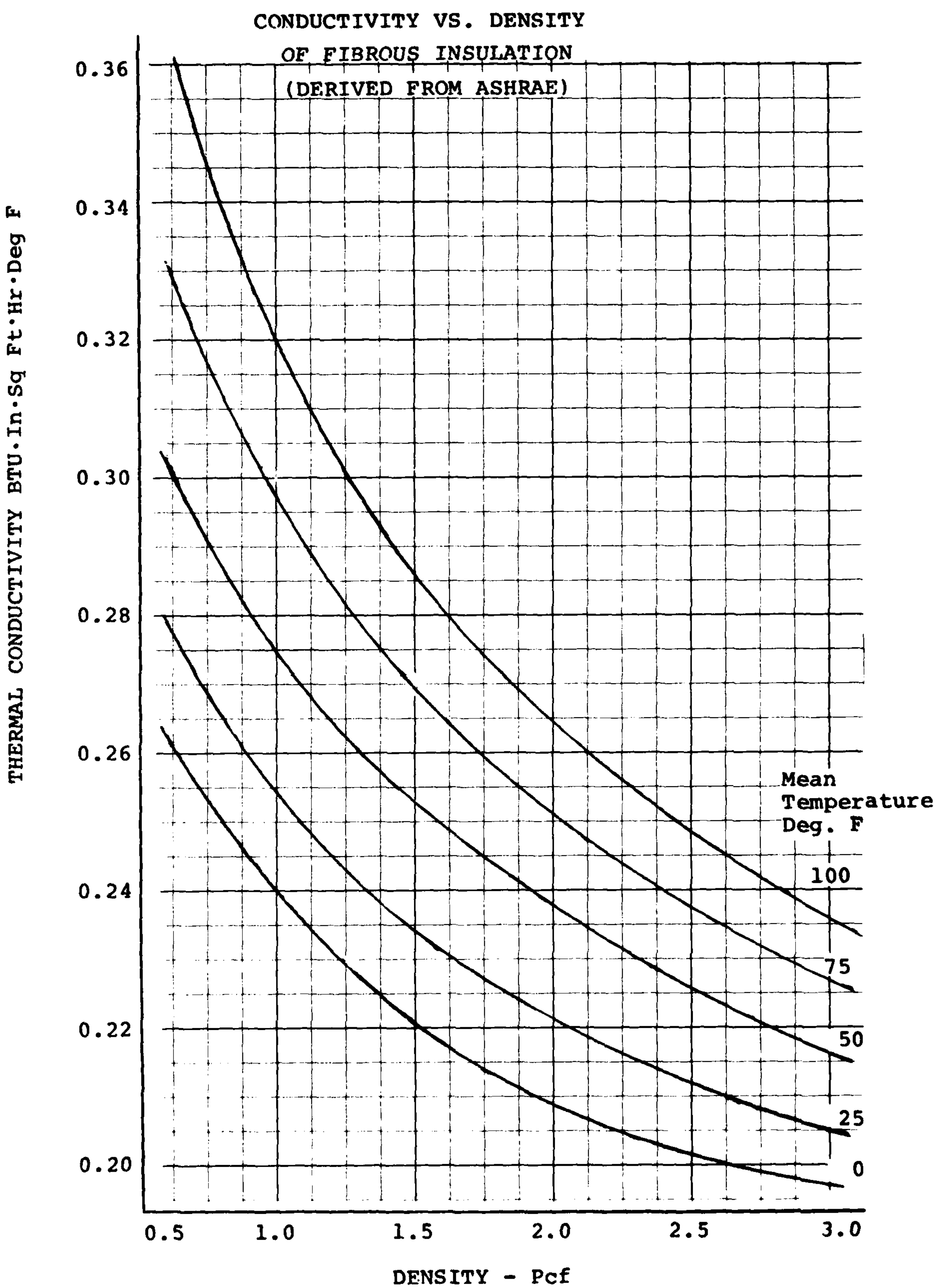
* λ = Thermal conductivity

** λ = 0.295 Btu·in./hr·ft^2·°F

*** λ = 0.285 Btu·in./hr·ft^2·°F

**** = R values calculated from present test data to permit comparisons at the appropriate thicknesses.

FIGURE 8



CONDUCTIVITY VS. DENSITY
OF FIBROUS INSULATION
(DERIVED FROM ASHRAE)
THERMAL CONDUCTIVITY BTU·In·Sq Ft·Hr·Deg F
0.36
0.34
0.32
0.30
0.28
0.26
0.24
0.22
0.20
Mean
Temperature
Deg. F
100
75
50
25
0
0.5
1.0
1.5
2.0
2.5
3.0
DENSITY - Pcf

valid for 1 inch thickness and may not apply to greater thickness. Slopes should be valid.

The test results on fiber glass insulation removed from the Type I panel indicate an apparent thermal conductivity of 0.295 when tested at 3.5 inches thick and a density of 0.79 pcf. This compares with an apparent thermal conductivity of 0.315 read from Figure 8. It is probable that the fiber diameter of the insulation tested is lower than that assumed for the design figures presented by ASHRAE. A smaller fiber diameter results in lower conductivity.

The test results on the insulation removed from the Type II panel indicate an apparent thermal conductivity of 0.285 when tested at 5.5 inches thick and a density of 0.87 pcf. This compares with an apparent thermal conductivity of 0.307 read from Figure 8.

The temperatures recorded for the Type II panel interior and exterior surfaces (to establish whether the surfaces could be considered isothermal) are presented in Figures 9 and 10 for the three mean temperatures at the 10 percent gap and for the two higher mean temperatures for the 15 percent gap. It will be seen that the maximum variation occurred at the warm surface and amounted to 6 degrees. That varied from 5 to 10 percent, depending on temperature. No definition of what limits should be set on temperature variation permitted where a plane may be defined as isothermal has been noted in the literature. A 10 percent maximum limit appears very reasonable so the surfaces of the present panels may be considered isothermal planes.

FIGURE 9

COMPARISON OF TEMPERATURE PROFILES
THROUGH 10% AIR GAP AND THROUGH
INSULATION FOR TYPE II PANEL

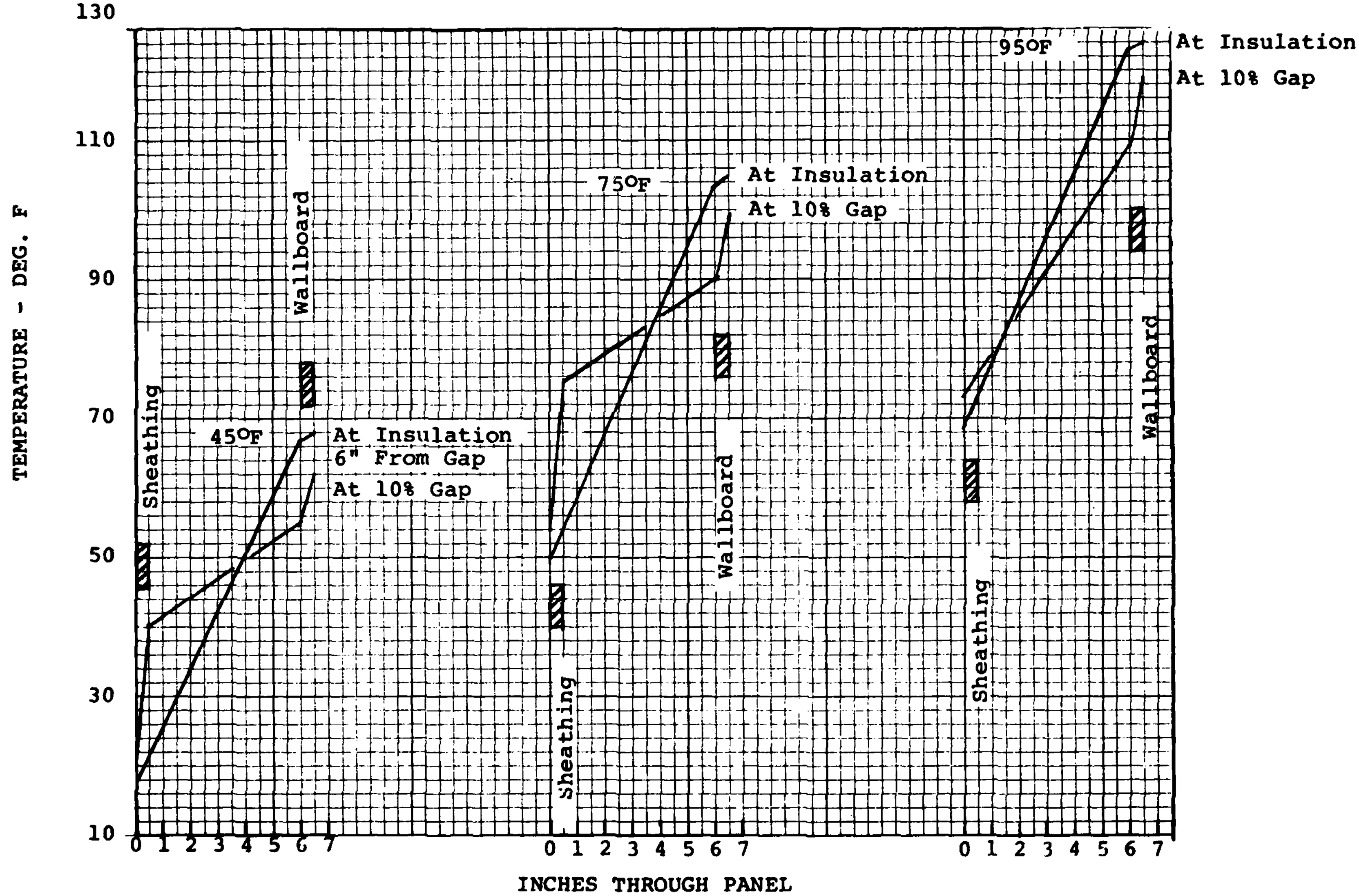
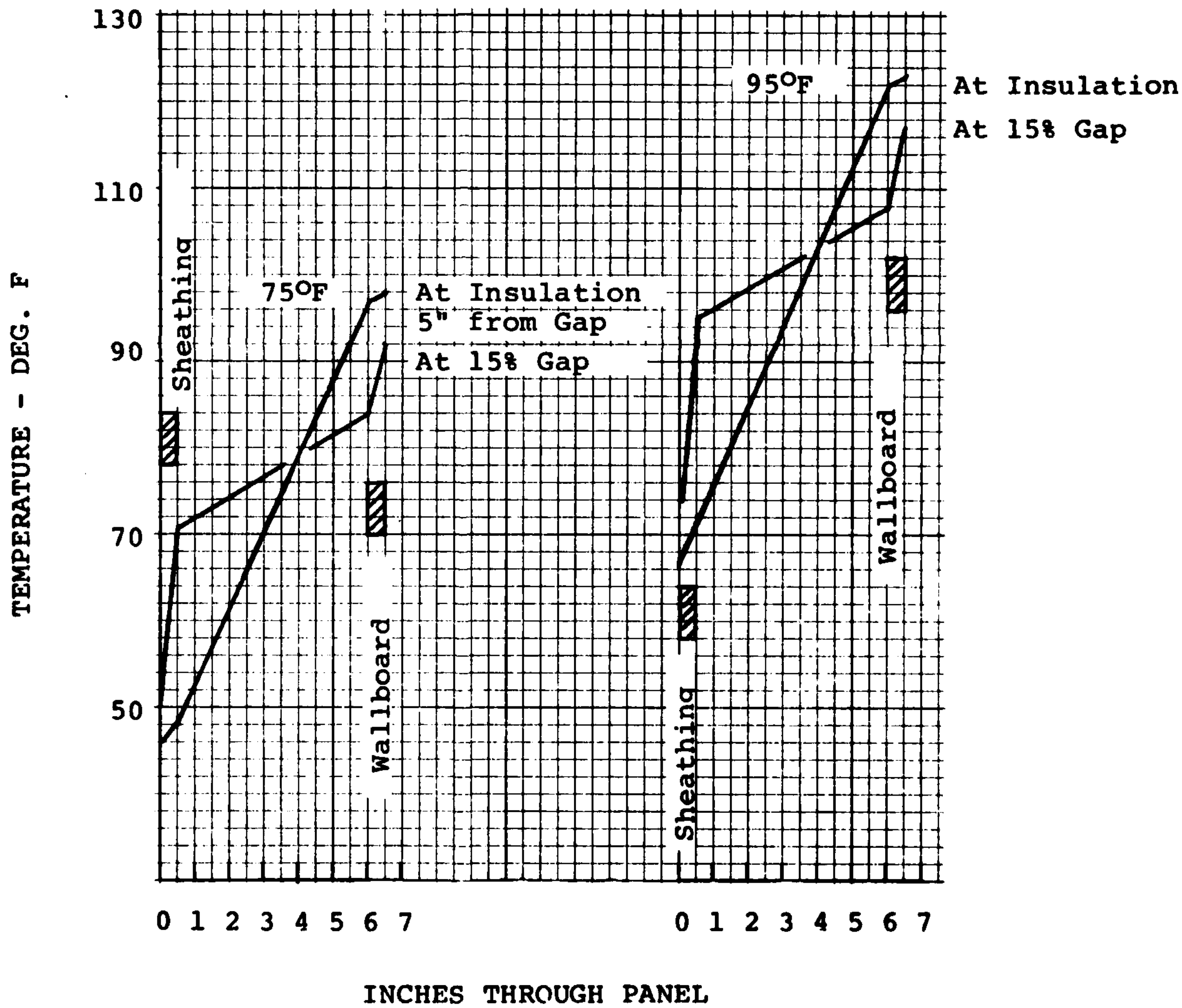


FIGURE 10

TEMPERATURE PROFILES THROUGH 15%
AIR GAP AND THROUGH INSULATION
FOR TYPE II PANEL



VARIABILITY OF RESULTS

The calculated thermal conductances were determined mainly from the average of 8 hourly readings. From the individual values, the standard deviation and plus or minus limits of the average were calculated for a probability of 0.95. Results are presented in Tables 13 and 14.

For the Type I panel, the temperatures varied ±0.3 degrees on the average for the confidence limit of the average. The mean confidence limit for thermal conductance was ±0.0010 while that for thermal resistance was ±0.10. The values seem comparable for the two types of panel with ±0.2 degree average confidence limit for Type II and with limits for conductance of ±0.0007 and ±0.13 for resistance.

A further measure of reproducibility of values may be determined from the replicated tests for the Type I panel with a 10 percent cut out at 75°F and 94°F mean temperatures. A comparison of values is shown in Table 15 below:

TABLE 15
REPRODUCIBILITY OF TYPE I PANEL
DATA FROM REPLICATED TESTS

Date	Mean Temperature °F	Thermal Conductance Btu/hr·ft^2·°F	Difference Between 4 Hr. Sets-%	Thermal Resistance °F·ft^2·hr/Btu
3/16/79	75.9	0.11516	0.63	8.7
3/28/79	76.3	0.11213	0.39	8.9
3/20/79	96.2	0.11714	0.43	8.5
3/21/79	96.6	0.11632	0.24	8.6

Both of these pairs meet ASTM C-236 requirement that the difference of the two 4 hour averages for conductance not exceed one percent. In each case the value selected for use in the report was that with the lower difference. The differences in thermal resistance of the two pairs of test values were 0.2 R or 2.3 percent and 0.1 R or 1.2 percent.

TABLE 13

VARIABILITY FOR TYPE I PANEL

Percent Gap	Temperature °F	Standard Deviation °F	Thermal Conductance BTU/hr·ft²·°F	Coefficient of Variation %	Thermal Resistance °F·ft²·hr/BTU
0	45.16 ± 0.24	0.10	0.0804±0.0011	0.32	12.44 ± 0.17
	75.96 ± 0.18	0.08	0.0865±0.0007	0.30	11.56 ± 0.10
	97.78 ± 0.19HFO	0.06	0.0931±0.0007	0.17	10.74 ± 0.08
	98.53 ± 0.18HFI	0.08	0.0932±0.0006	0.58	10.73 ± 0.07
5	45.16 ± 0.29	0.12	0.0945±0.0010	0.24	10.58 ± 0.12
	75.54 ± 0.27	0.12	0.1018±0.0008	0.33	9.82 ± 0.08
	96.04 ± 0.09	0.04	0.1089±0.0011	0.29	9.18 ± 0.10
10	45.94 ± 0.31	0.13	0.1082±0.0005	0.44	9.24 ± 0.05
	76.25 ± 0.43	0.18	0.1119±0.0024	0.32	8.94 ± 0.19
	96.55 ± 0.27	0.11	0.1168±0.0015	0.45	8.56 ± 0.11
15	45.31 ± 0.34	0.14	0.1110±0.0009	0.21	9.01 ± 0.07
	75.44 ± 0.33	0.14	0.1193±0.0009	0.91	8.38 ± 0.07
	93.78 ± 0.16	0.07	0.1247±0.0005	0.56	8.02 ± 0.03
Average	± 0.27	0.11	±0.0010	0.39	± 0.10

TABLE 14
VARIABILITY FOR TYPE II PANEL

Percent Gap	Temperature °F	Standard Deviation, °F	Thermal Conductance	Coefficient of Variation - %	Thermal Resistance
0	47.13±0.10	0.19	0.0556 ± 0.0002	0.13	17.99 ± 0.07
	76.58±0.10	0.18	0.0609 ± 0.0009	0.66	16.42 ± 0.25
	97.85±0.07	0.08	0.0651 ± 0.0005	0.31	15.36 ± 0.12
5	43.17±0.04	0.05	0.0684 ± 0.0021	0.13	14.62 ± 0.45
	77.19±0.04	0.05	0.0766 ± 0.0003	0.17	13.05 ± 0.06
	97.65±0.18	0.33	0.0818 ± 0.0009	0.49	12.22 ± 0.14
10	43.26±0.05	0.08	0.0778 ± 0.0004	0.19	12.85 ± 0.07
	77.96±0.05	0.07	0.0866 ± 0.0004	0.20	11.55 ± 0.06
	96.25±0.14	0.23	0.0915 ± 0.0004	0.16	10.93 ± 0.05
15	41.73±0.01	0.13	0.0870 ± 0.0012	0.57	11.49 ± 0.16
	72.85±0.09	0.17	0.0976 ± 0.0005	0.20	10.25 ± 0.05
	96.32±0.08	0.12	0.1027 ± 0.0007	0.29	9.74 ± 0.07
Average	0.08	0.14	± 0.0007	0.29	± 0.13

The noted differences in test values were those existing with the same operator making eight sets of readings and performing the required calculations. The differences due to operators or to setting of the test panel in the apparatus are not included.

ANALYSIS OF RESULTS

Table 10 presents surface to surface thermal resistance values for Type I walls interpolated to the 3 nominal mean temperatures and with gaps expressed as a percentage of insulated area. Those 5, 10, and 15 percent areas would be 4.6, 9.1, and 13.6 percent of gross area.

For the condition of 75°F mean temperature, full insulation, R values based on data generated by actual testing, and using parallel heat flow theory, the calculated surface to surface thermal resistance is 12.1. This compares with a test value of 11.6 and is 0.5 R or 4.3 percent higher.

Under the same assumptions but with a 5 percent gap (insulation area) the calculated R is 11.6 compared to a test value of 9.8. This is a difference of 1.8 R or 18.4 percent between calculated and test values. If, for the 5 percent gap, the assumption of isothermal surface planes is made, the calculated R is 8.6 which is 1.2 or 14 percent lower than as tested.

It may be seen that standard methods of calculation for thermal resistance are reasonably close for full insulated, R-11 conditions, but do not provide adequate accuracy when thermal insulation gaps are assumed. This appears contradictory to the conclusion in Report No. CR 78.006 based on a single test with a gap size somewhat below 5 percent of the insulation area.

The Type I panel with full insulation had been tested previously for Report CR 78.006. The R values compare as shown in Table 16.

TABLE 16

COMPARISON OF PREVIOUS AND PRESENT TYPE I PANEL DATA

THERMAL RESISTANCE AT INDICATED MEAN TEMPERATURE

$^{\circ}F \cdot ft^2 \cdot hr/Btu$

	45°F	75°F	95°F
CR 78.006	11.9	10.9	10.0
Present Tests	12.4	11.6	10.9

The present test values were higher by a maximum of 0.9 R. This difference parallels that noted for the standard test specimen reported in the Test Procedure Section. That specimen increased 0.89 in measured R at 40°F mean temperature over a 3 year period. The previous discussion of standard specimen results should also apply to the present results.

Figure 6, presented in the Test Results section, shows the variation in thermal resistance with gap area and mean temperature for the Type I panel. Note the slope of the curves for full insulation and for the 5 percent gap (insulation area) are comparable. At 10 and 15 percent gaps, the slope is much lower. Because of the marked difference in slope, the 75°F and 95°F mean temperature points for the 10 percent gap were independently rechecked a second time. The second results were close to those first obtained with any slight difference leading to a more valid straight line relationship (see Table 15).

It will be seen in Figure 7, which presents results for the Type II panel, that the 10 and 15 percent gaps also show lesser slopes than the full insulation test results or the 5 percent gap test results. Table 10 presents surface to surface resistance values for Type II panels.

It will also be noted that the effect of gaps is much more detrimental in terms of decreased thermal resistance for the Type II panel than for the Type I panel. A loss of 3 to 3-1/2 R (28 percent) for a 15 percent gap is noted for the Type I panel. The Type II panel shows a loss of 6.7 R (37 percent). The higher loss is not unexpected.

The maximum thermal resistance for the Type II wall with no gap at 75°F mean temperature was 16.5. A 6 inch thick insulation is usually rated at R-19. When installed in a 2 X 6 inch stud wall, the insulation is compressed to 5-1/2 inches which will densify the product, improving the thermal conductivity by 0.01 unit, but reducing thickness by 1/2 inch, which reduces the thermal resistance by 1.6 R.

When thermal resistance of a Type II wall is calculated by parallel heat flow theory, using the actual resistance values determined for these components, the surface to surface R is 20.1. When calculated with the assumption of isothermal planes on each surface the R is 19.0. That is 2.5 R or 15 percent higher than that tested. The calculations for the various gaps are still further distant from the test values.
Report No. CR 78.006 also showed less agreement between the

calculated and test values for R-19 ceiling systems. Hence, the extent of agreement may be a function of R value.

Therefore, theory as presently available does not adequately permit calculation of the effect of insulation gaps up to 15 percent for either wall tested.

Figure 11 presents the data developed by the present tests in a form which should be useful for estimation of the decrease in thermal resistance caused by gap areas in thin and thick insulation. With reasonable care in installation the gaps should not exceed 5 percent. The loss for each type of wall is linear for that range, although the slope differs for each type. For Type I walls the decrease in value is 0.385 R per percent gap. For Type II walls, the decrease is 0.75 R per percent gap.

All discussions of test results have been on the basis of surface to surface thermal resistance. This ignores the air film resistances and the resistance of whatever exterior siding is installed. The final cost of heating or cooling a structure is based on the U_o value which takes into account all elements of a structure, walls, floors, roofs, doors and windows, etc. A significant portion of the heat loss is through walls and we have seen that insulation gaps may significantly increase that loss.

For example, consider a Type I wall during the heating season. Assume that lapped wood bevel siding 0.5 X 8 inches is applied to the outer surface of the walls. ASHRAE cites a resistance of 0.81 for that siding and an exterior surface resistance of 0.17 (assuming a 15 mph wind) with an interior surface resistance of 0.68. For 45°F mean temperature and no gap the thermal transmission based on Figure 11 values, would be:

$U = 0.076$ BTU·hr·ft^2/deg F for 45°F mean temperature

For a gap of 5 percent of the gross area:

$U = 0.083$

This is an increase of 9.2 percent.

On the basis of a small, 1370 square foot ranch house with a gross wall area of 1480 square feet, the heat loss would be:

U = 116,724 BTU per day for no gaps

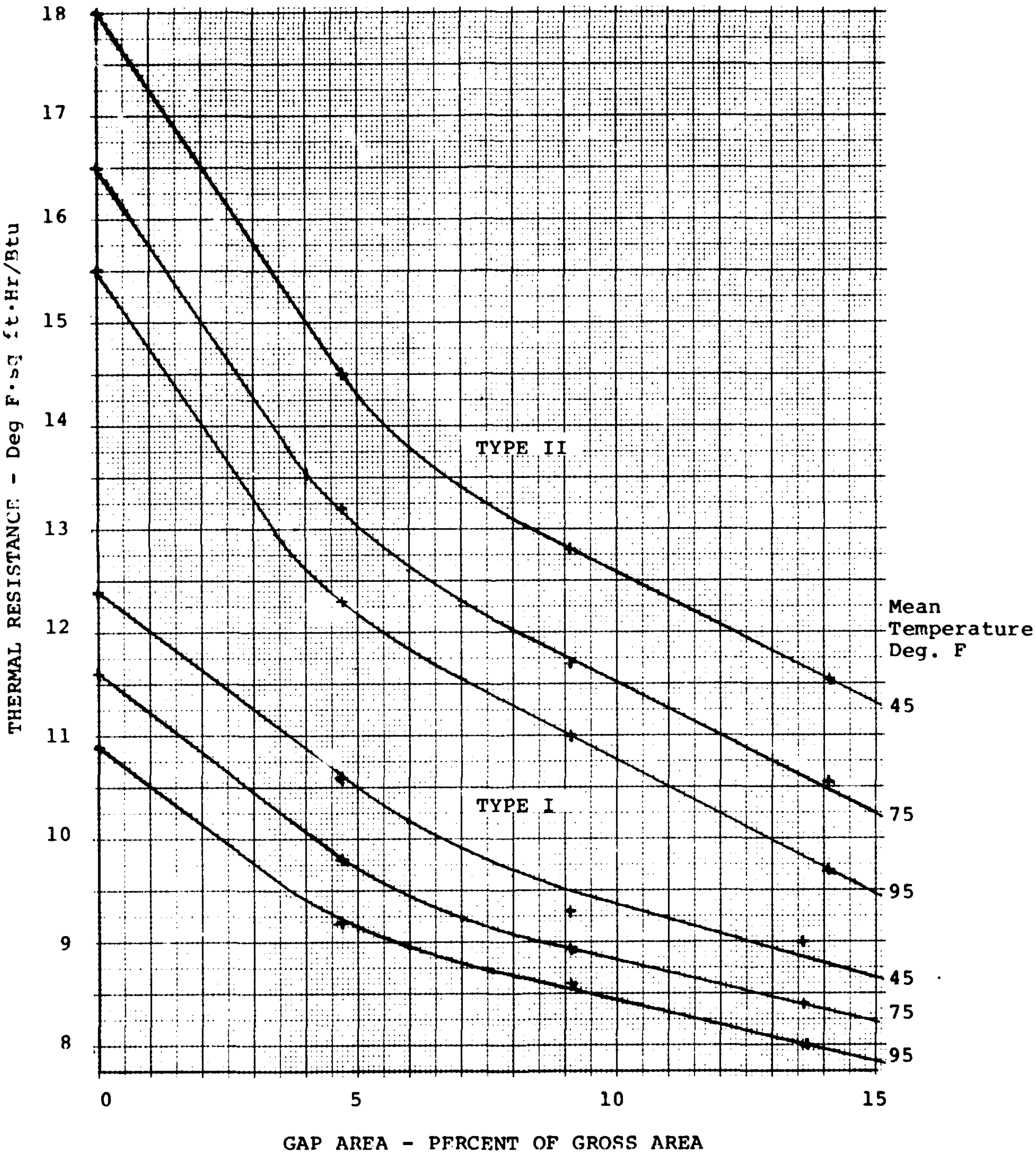
U = 136,452 BTU per day for 5 percent gap or an increase of 19,728 BTU.

For a 15 percent gap under the same condition, the U would be 172,171 BTU or an increase of 55,558 BTU (48 percent).

This example is illustrative only. No account was taken of doors and windows with their higher heat loss, heat loss through the other house elements, or the effect of air infiltration.

A Type II wall would be more seriously effected by insulation gaps of similar sizes. A 5 percent gap would increase heat loss 23 percent while a 15 percent gap would cause an increase of 55 percent.

FIGURE 11
EFFECT OF AREA OF GAP
ON THERMAL RESISTANCE



CONCLUSIONS

1. Small gaps in insulation will significantly increase heat loss through a wall. The increase will be higher than the gap expressed as a percentage of the area and will be much greater for walls of higher resistance.

2. Conventional methods of calculation of the thermal resistance of walls agreed reasonably well with test results for 2 X 4 stud walls with R-11 fiber glass insulation. The calculated value was 15 percent high for 2 X 6 stud walls with R-19 insulation installed. Neither were conventional methods of calculation adequate for determination of the decreased thermal resistance of a wall due to existing gaps in the insulation.

3. The design values presented by ASHRAE for wood fiber sheathing, gypsum wallboard, wood studs, and mineral fiber insulation are reasonable averages. Greater precision in calculation of overall resistance may be obtained if values for the actual component are substituted for the design values.

4. The effect of mean temperature on the thermal resistance of wood fiber sheathing, gypsum wallboard, and fir wood was not found significant between 75°F and 120°F mean temperature. The effect on fiber glass blanket was not determined by test but ASHRAE indicates a 9 percent decrease between 75°F and 100°F and an 8 percent increase between 75°F and 50°F.

5. No significant effect of the direction of heat flow (inward or outward) at 95°F mean temperature was noted for 2 X 6 stud walls with R-19 insulation as tested without gaps. This may be expected because of the minor influence of temperature upon the thermal properties of wood fiber sheathing and gypsum wallboard. Similar lack of effect would be presumed to exist for building materials greater than 15 pcf in density.

6. Panel materials such as gypsum wallboard and wood fiber sheathing may be presumed to provide essentially isothermal planes in insulated walls. It is recognized, however, that non-uniformity of temperature can exist, particularly where insulation gaps occur.

7. Estimates of test variability derived statistically for each test from the eight individual readings of temperature and power input gave an average standard deviation for mean temperature of 0.13 percent. Maximum was 0.33 and minimum 0.04 percent. Coefficient of variation for conductance averaged 0.29 to 0.39 percent for the two tests. The average limits of uncertainty of the mean value for conductance were 0.0007 and 0.0010 $BTU/hr \cdot ft^2 \cdot {}^oF$ for the two tests. The corresponding limits of uncertainty of the mean for thermal resistance were 0.10 and 0.13 ${}^oF \cdot ft^2 \cdot hr/BTU$ for the two tests.

8. Actual repeat tests on the Type I panel at 75^oF and 95^oF mean temperatures yielded R value differences of 0.2 and 0.1 ${}^oF \cdot ft^2 \cdot hr/BTU$ respectively. This represents variations of only about 1 to 2 percent.

APPENDIX A

PHOTOGRAPHIC ILLUSTRATIONS

LIST OF PHOTOGRAPHS

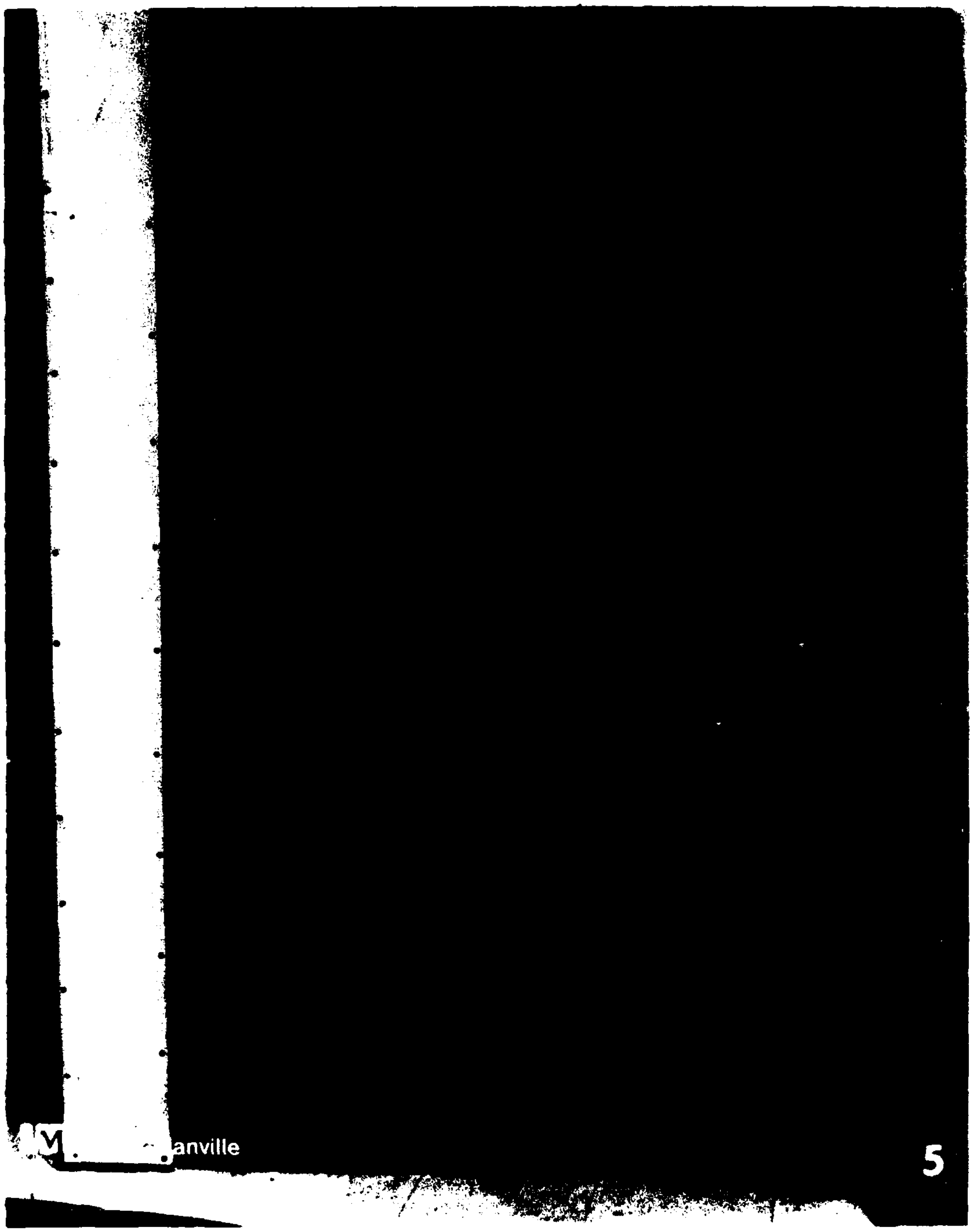
Identification		
Photo Number	Test Panel Type	Detail
1	-	Exterior of Guarded Hot Box
2	-	Controls for Guarded Hot Box
3	-	Cold side of box. Cooling coils and circulation fan are behind the plywood baffle.
4	I	Panel and interior of Guarded Hot Box showing metering and guard areas.
5	I	View of gypsum wallboard face of Type I panel with center wallboard section removed.
6	I	Same panel after 5 percent of insulation was cut-out.
7	I	Close-up of 5 percent cut-out.
8	I	Close-up of 10 percent cut-out.
9	I	Close-up of 15 percent cut-out.
10	II	View of gypsum wallboard face of Type II panel with center wallboard section removed.
11	II	Same panel after 5 percent of insulation was cut-out.
12	II	Close-up of 10 percent cut-out.
13	II	Full length view of 10 percent cut-out.
14	II	Full length view of 15 percent cut-out.
15	II	Close-up of 15 percent cut-out.
16	II	Wood fiber sheathing face of panel.

Photograph 1

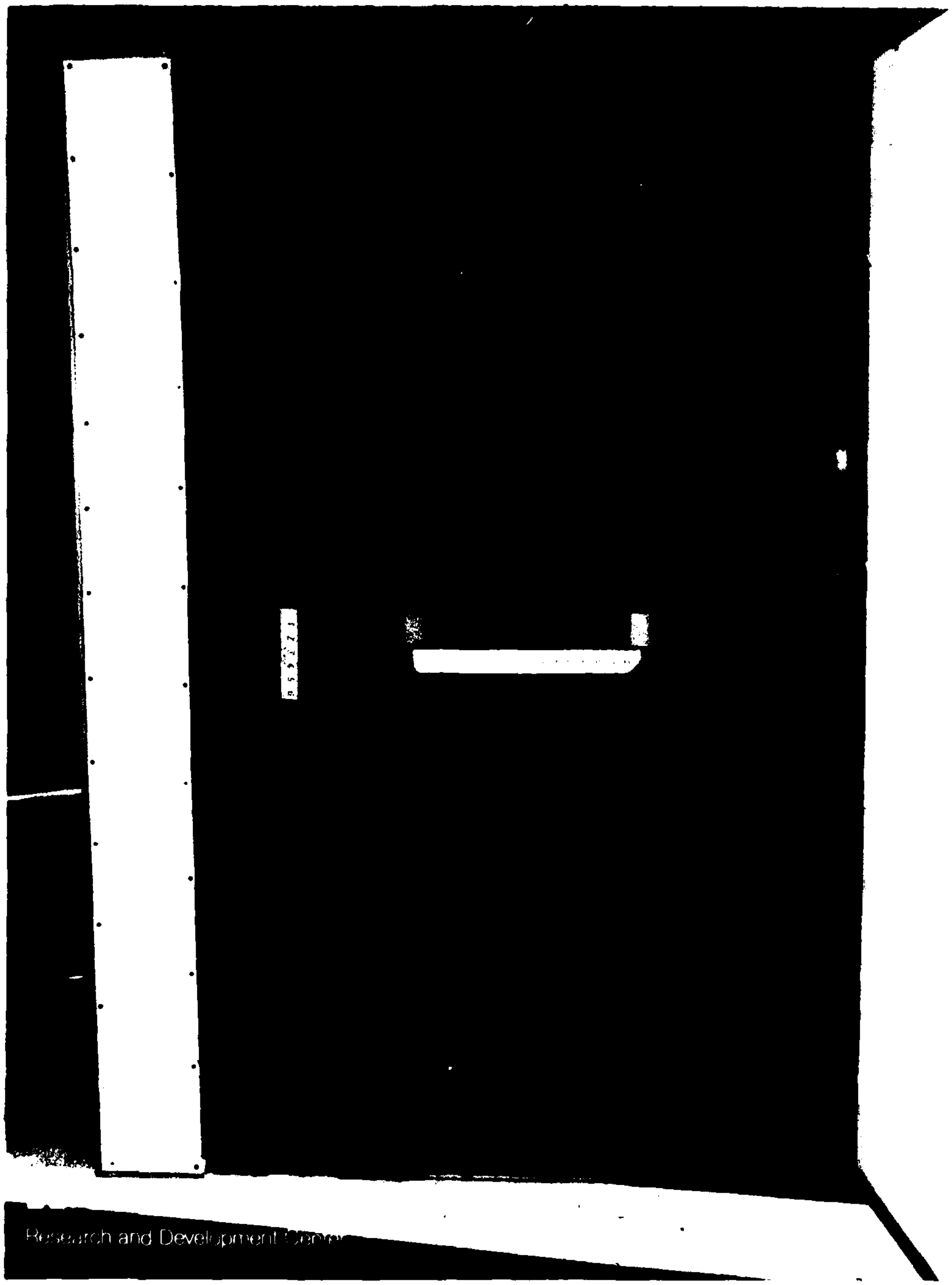
Photograph 2

Photograph 3

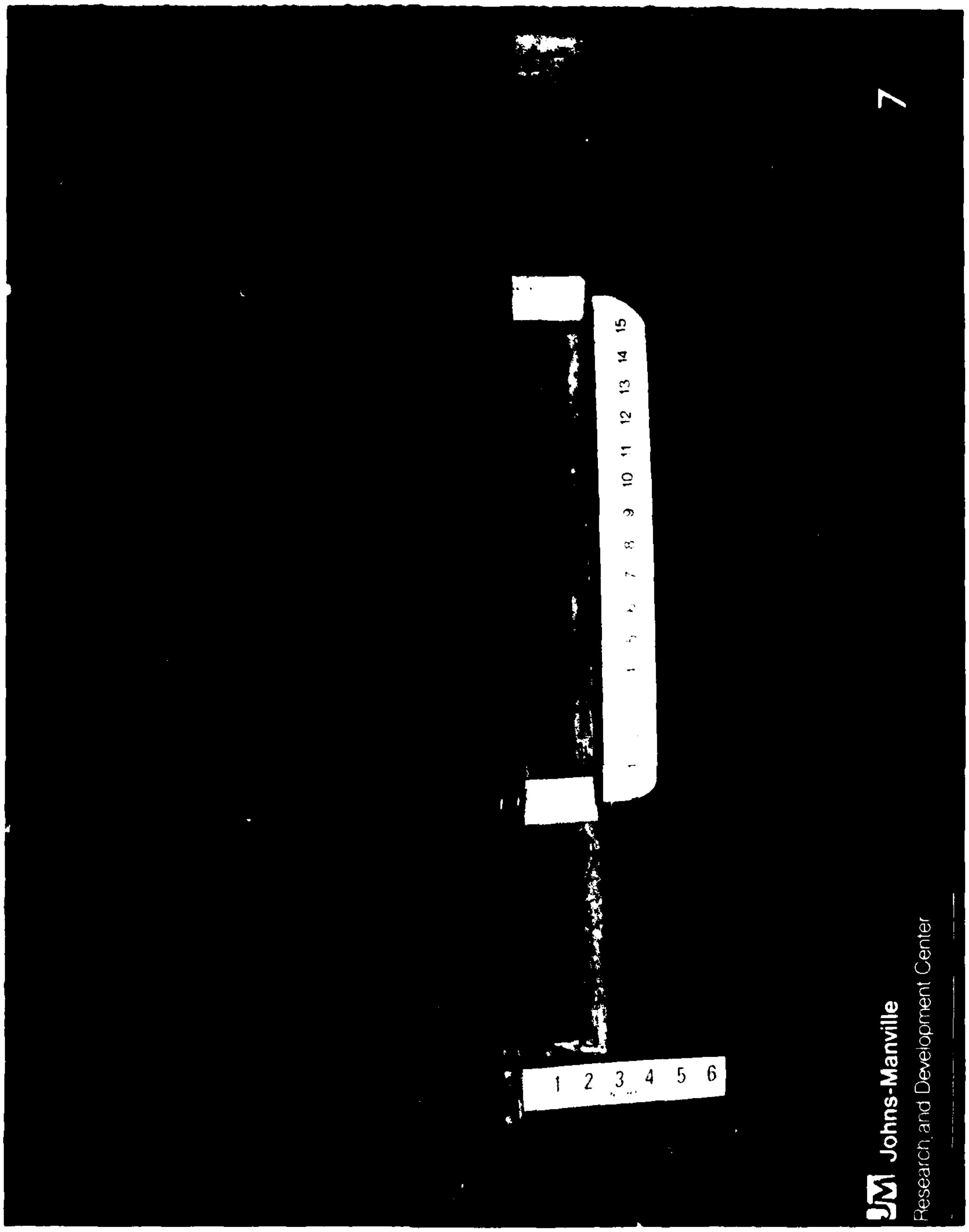
Photograph 4



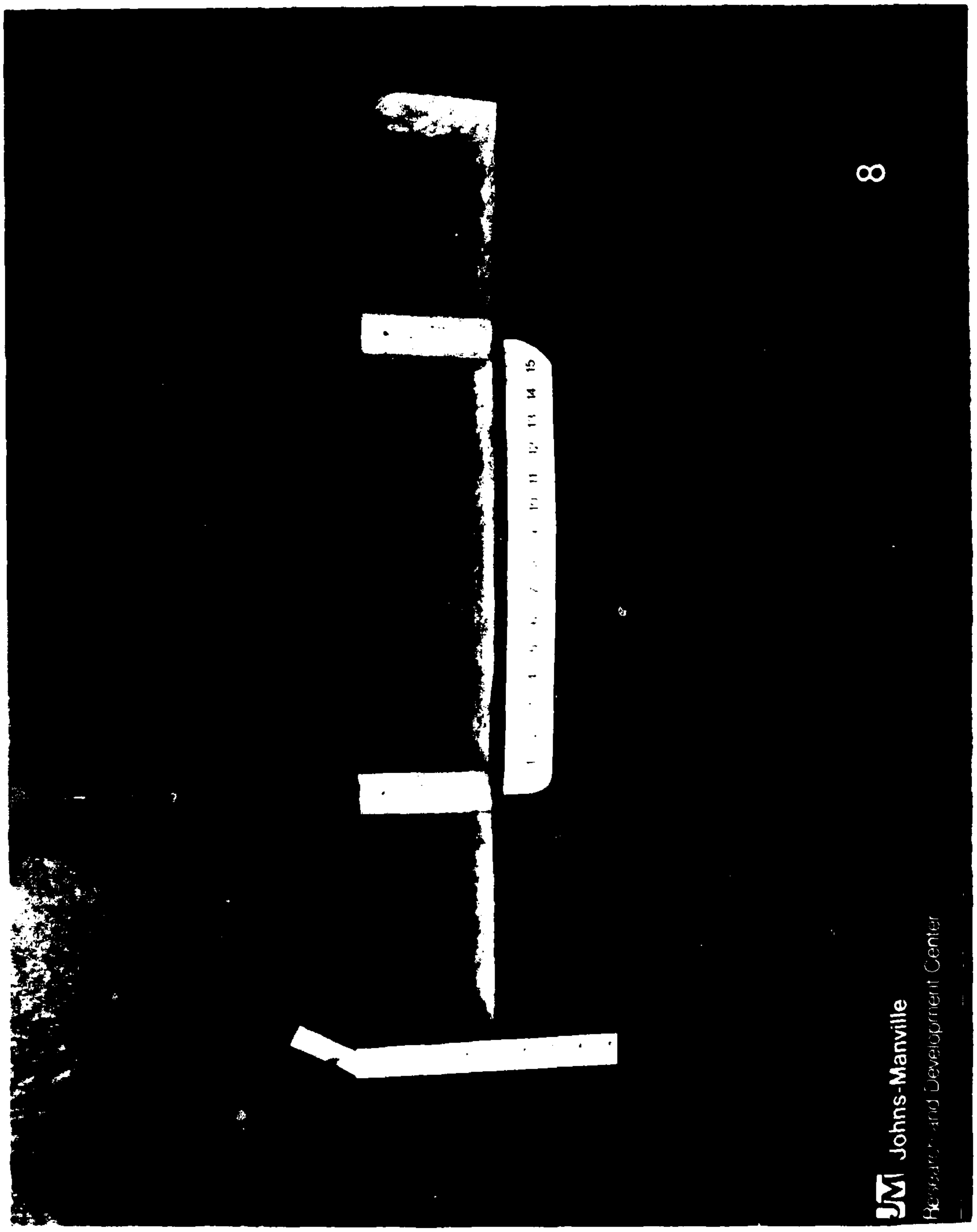
Photograph 5



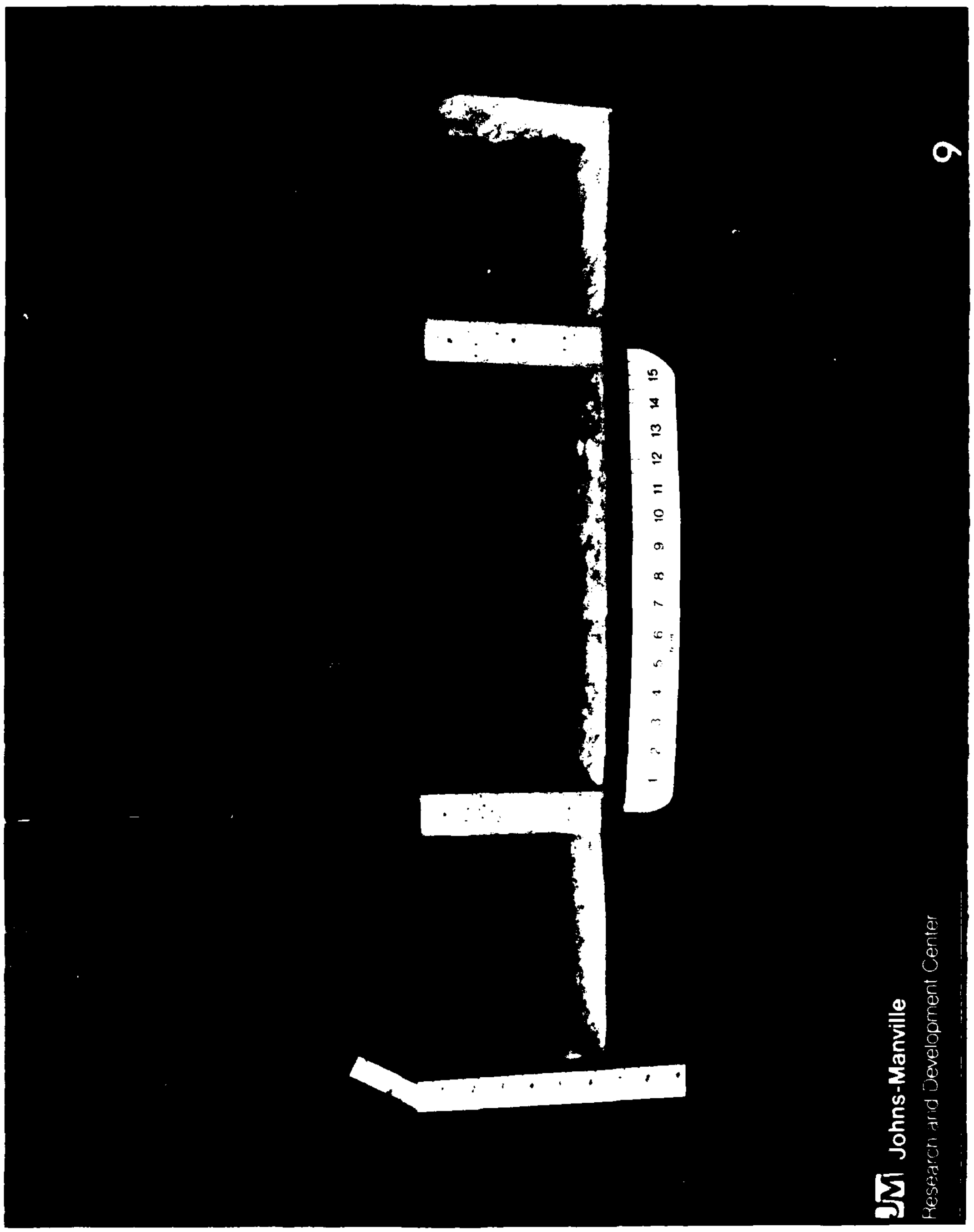
Photograph 6



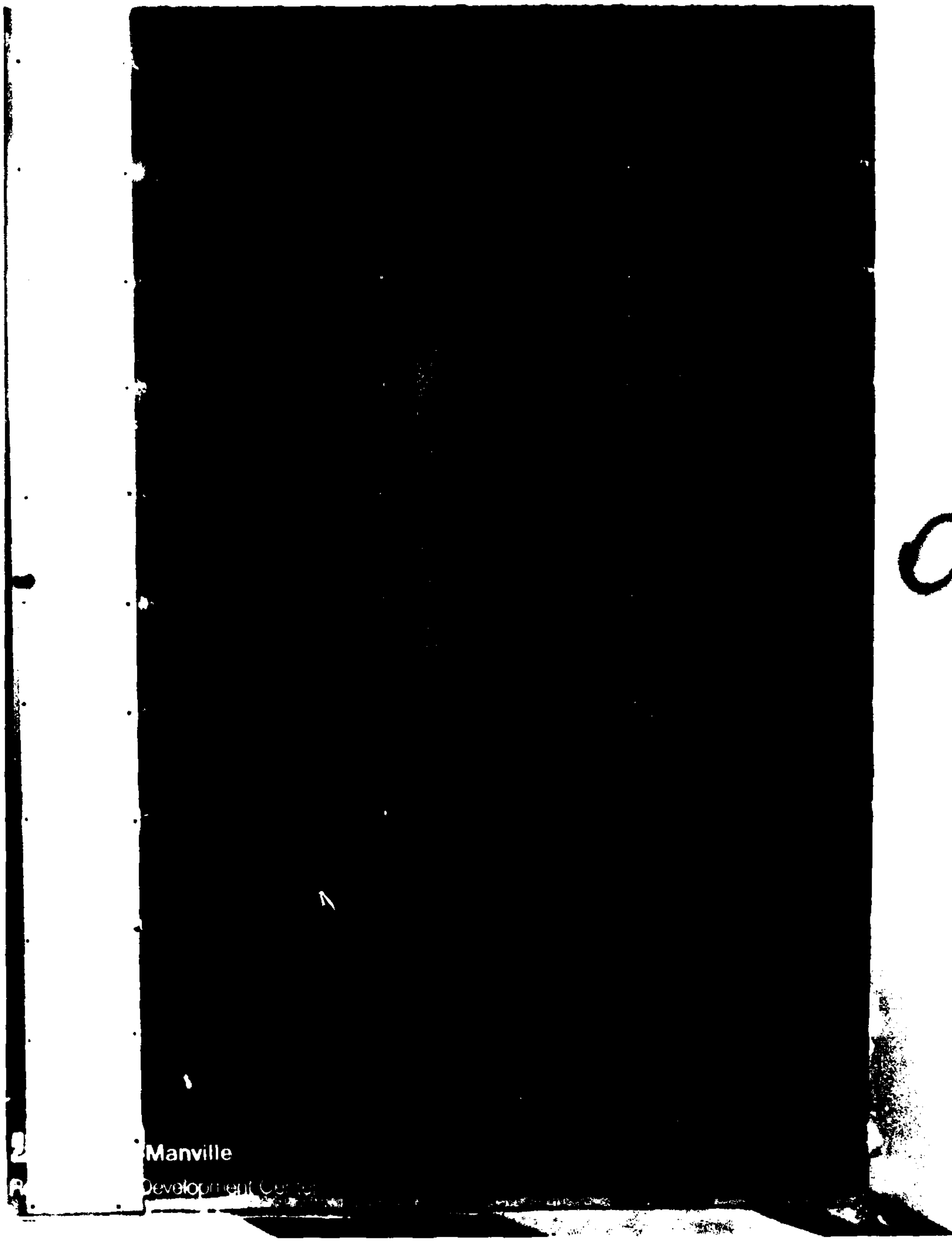
Photograph 7



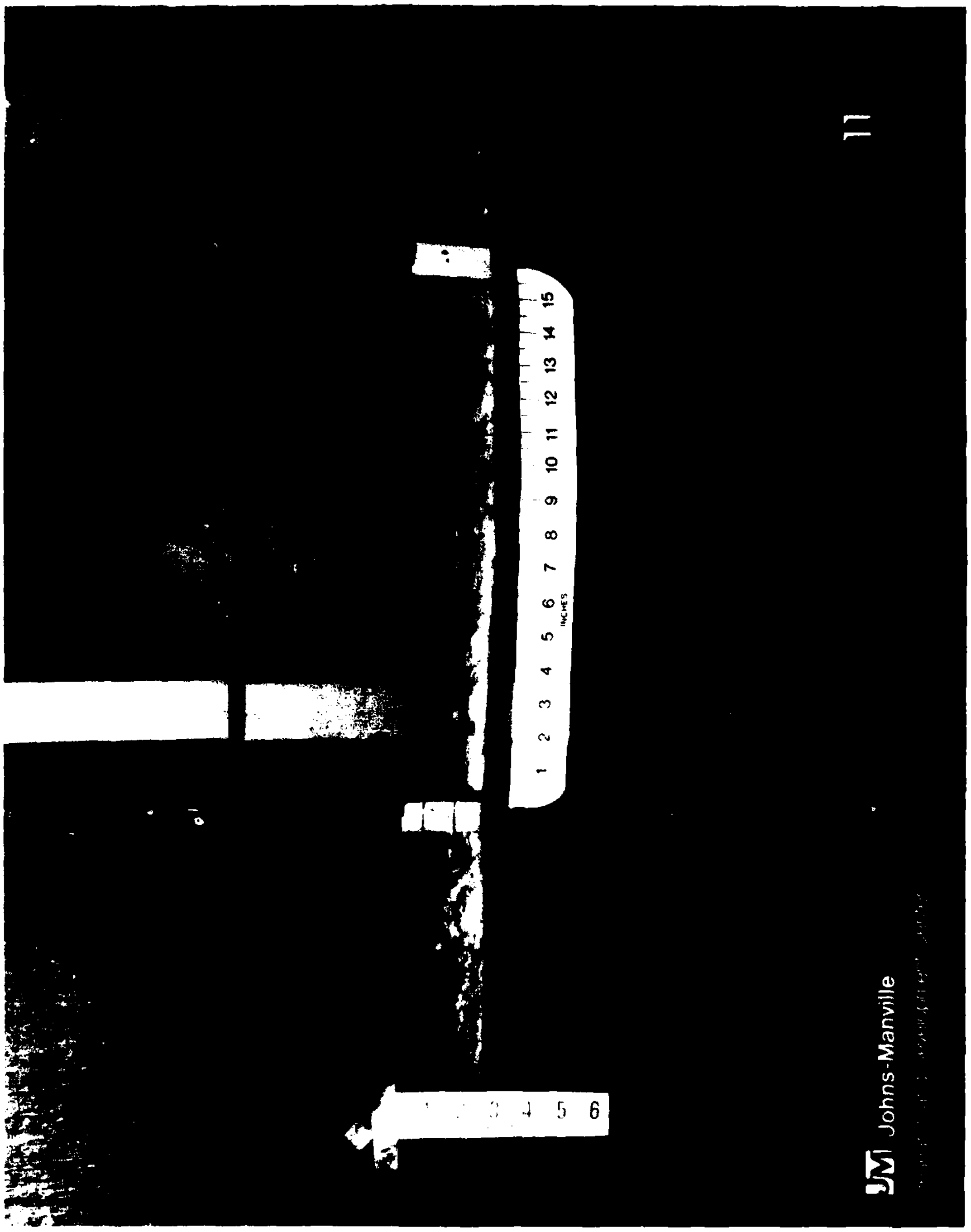
Photograph 8



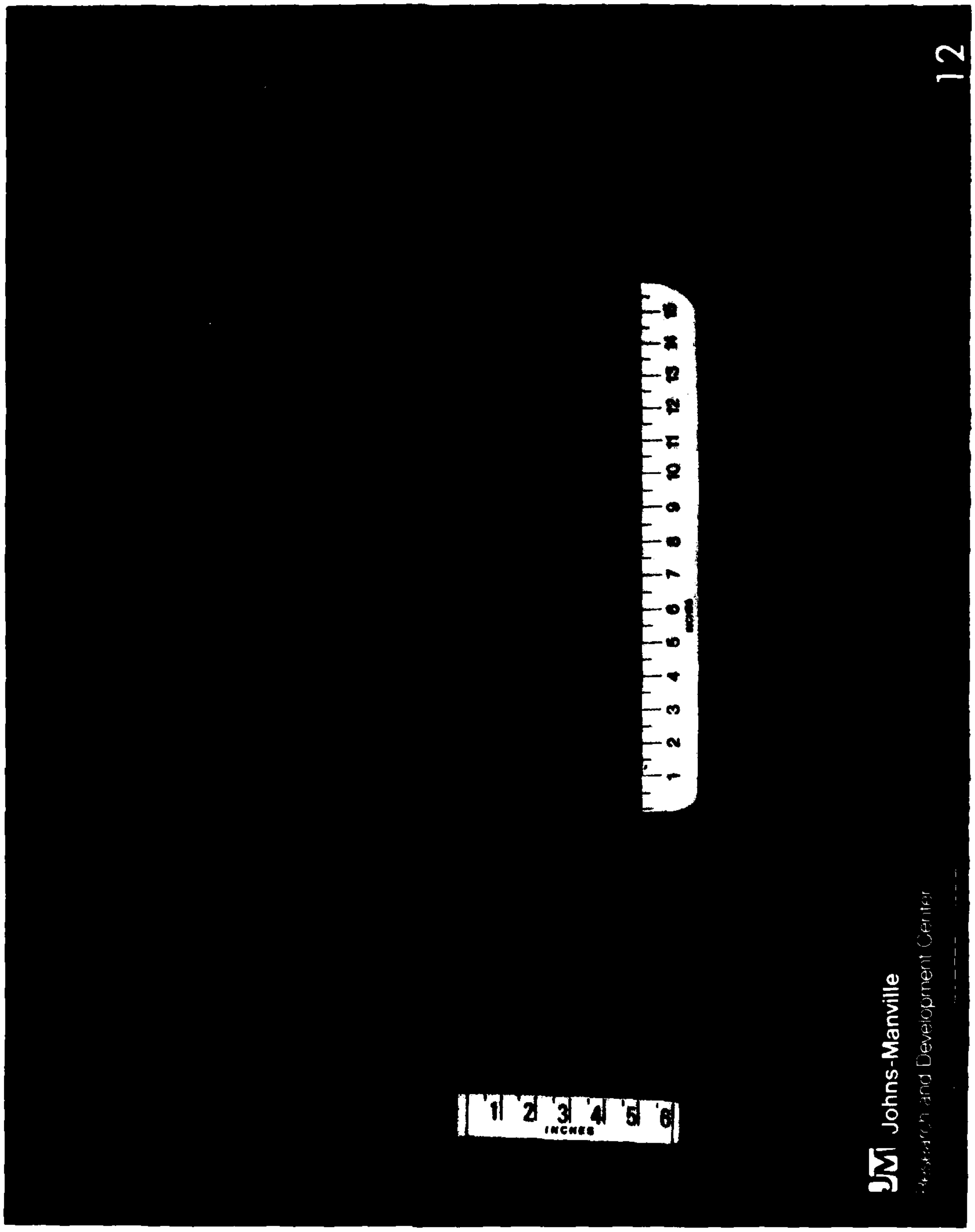
Photograph 9



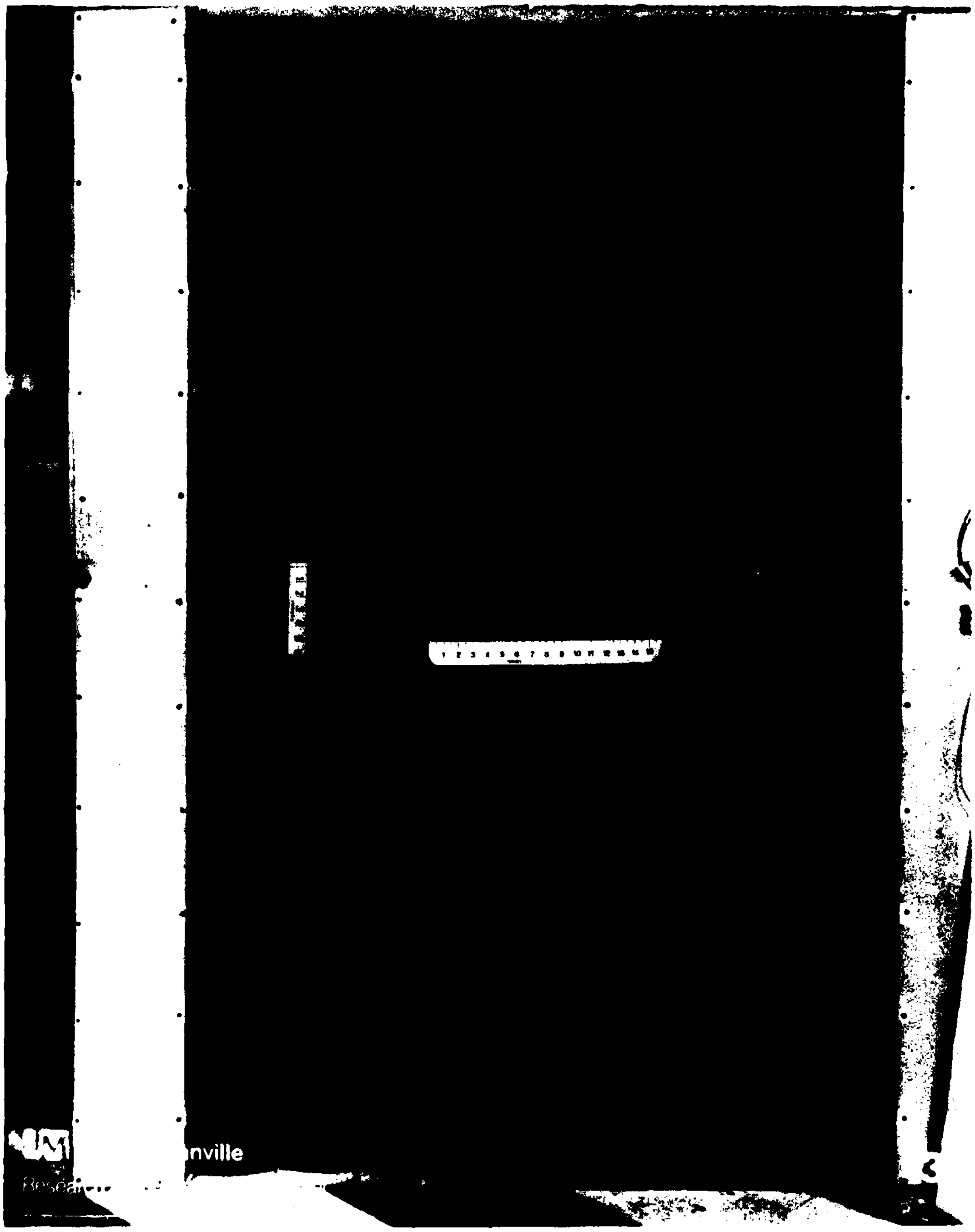
Photograph 10



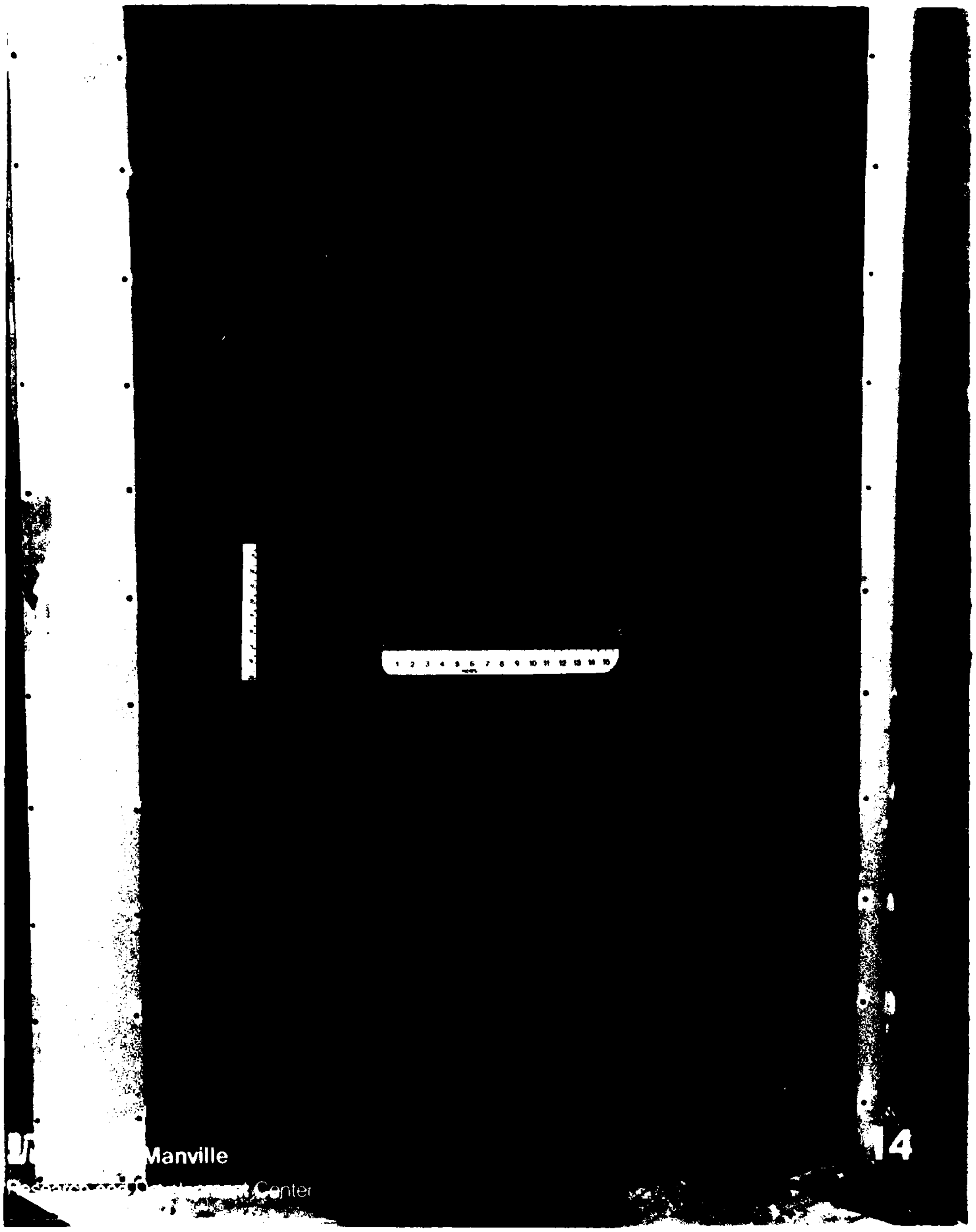
Photograph 11



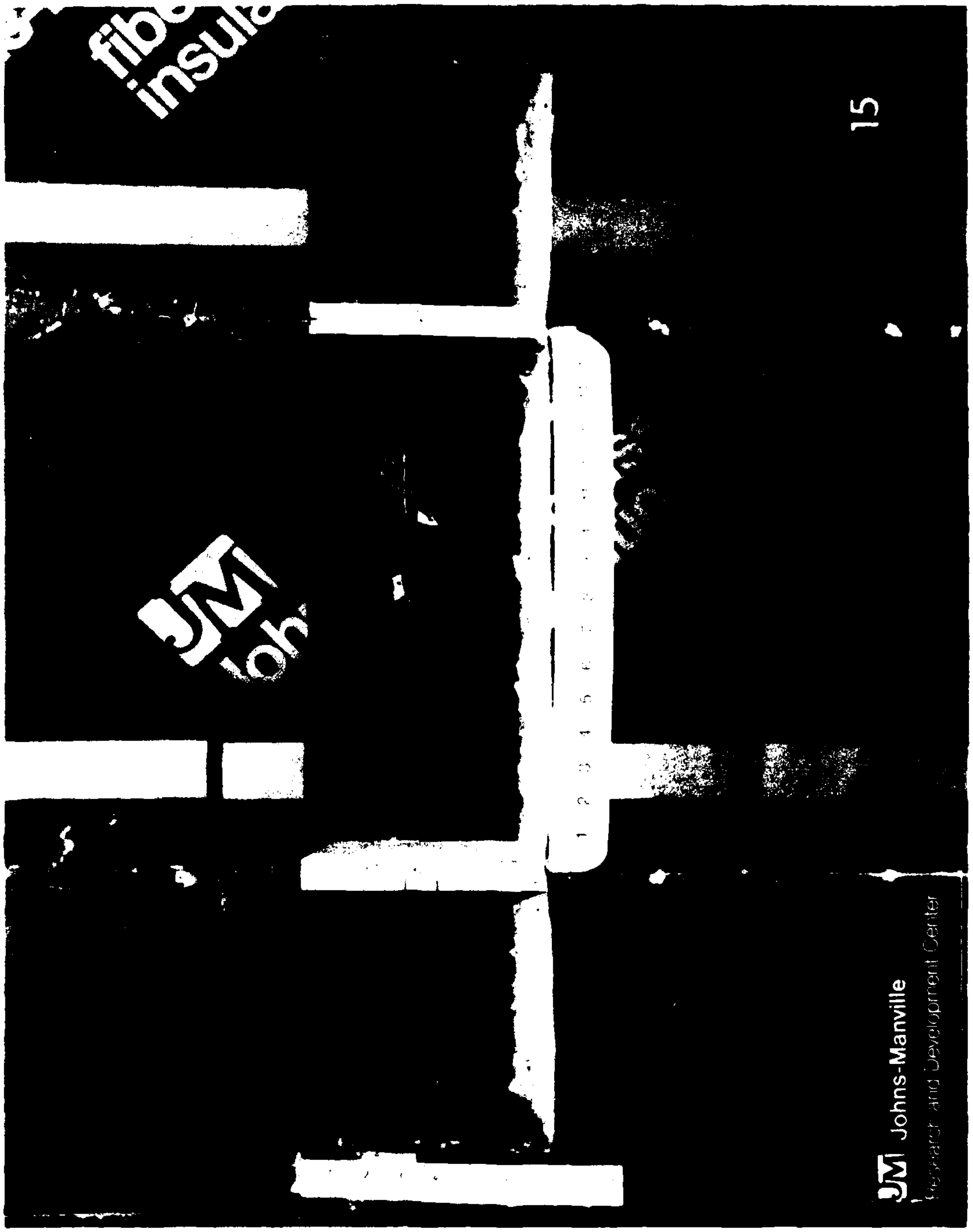
Photograph 12



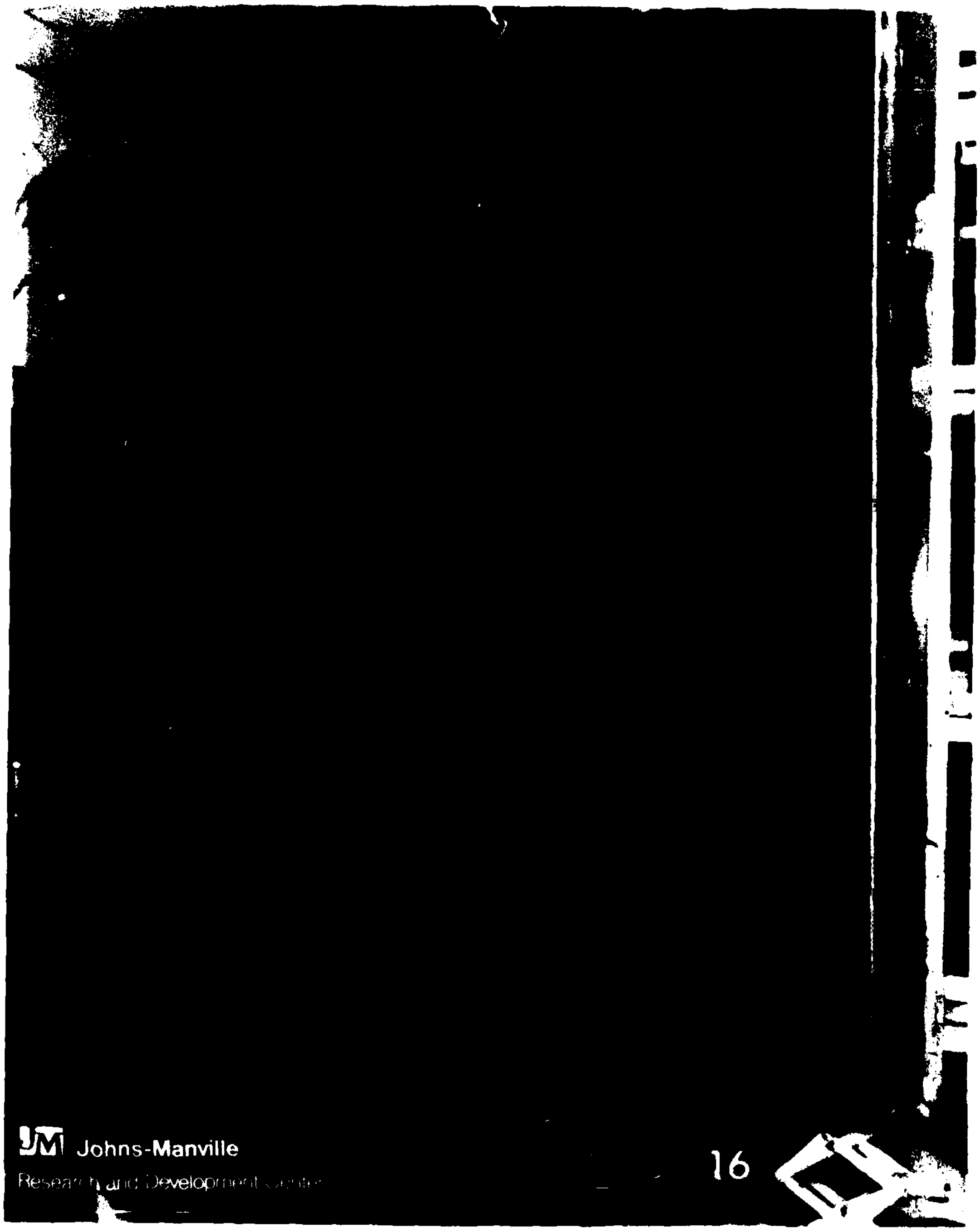
Photograph 13



Photograph 14



Photograph 15



Photograph 16

APPENDIX B

CEL Contract Report CR 78.006, "Effectiveness of Building Insulation Application", Johns-Manville Sales Corporation is available from the National Technical Information Service, Order Number AD-A053 452/95T.

The test program included Guarded Hot Box tests on 2 x 4 inch, 16 inch on center, wood stud panels with 1/2 inch wood fiberboard sheathing and 1/2 inch gypsum wallboard interior faces. Separate panels were tested as follows:

1. Without flaws in R-11 fiber glass blankets and tested at 45, 75, and 95°F mean temperature.

2. As 1 but with a 2 inch midheight gap for 3.8 percent of gross area.

3. As 1 but with insertion of an electric box, wiring and receptacle.

4. Without flaws in R-7 fiber glass blankets and tested at 45, 75, and 95°F mean temperatures.

5. As 4 but 1 inch top and bottom gaps and/or electrical box, wiring, and receptacle.

A ceiling of 2 x 6 inch joists, 16 inches on center with a 1/2 inch gypsum wallboard ceiling and R-19 fiber glass blankets was also tested without flaws; with a 3.8 percent gap; with a 1 inch overlap of insulation; and with an electrical box, wiring, and ceiling fixture. The panel without flaws was tested at 45, 75, and 95°F mean temperatures and the first two were tested with heat flow upward. The 75°F test was repeated with heat flow downward and the 95°F test was performed with heat flow down as is proper for summer conditions. The flawed ceiling panels were tested only at 45°F mean temperature, as was done with the flawed wall panels.

For the 2 x 4 inch walls without flaw and with the 3.8 percent insulation gap it was concluded that conventional calculation methods were adequate at 75°F mean temperature.

TABLE B-1

SUMMARY OF R-VALUES FOR CONSTRUCTION WITH ANOMOLIES

(Btu^{-1}/hr./sq.ft./^{o}F)

Mean Temperature = 45^{o}F

R-11 Wall, 3.8% void	11.5 (13%)*
R-7 Wall, 3.8% void **	7.2 (38%)
R-19 Ceiling, 3.8% void	14.4 (34%)
R-11 Wall, Electrical Box	13.2 (nil)
R-7 Wall, Electrical Box	10.4 (9%)
R-19 Ceiling, Electrical Box	20.8 (nil)

* Numbers in () are the decrease in the R value over panel without anomolie.

** Insulation centered in stud cavity, void area divided between top and bottom of test panel.

APPENDIX C

The test programs were conducted almost entirely by Aaron Garvin and Barbee Lunde. Assistance as needed was provided by the staff of the Thermal Conductivity Laboratory of the Johns-Manville Research and Development Center.